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Title: Development of a Novel 3D Acoustic Borehole Integrity Monitoring System

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Development of a Novel 3D Acoustic Borehole Integrity Monitoring System

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Los Alamos National Laboratory

- 11,300 employees
- 1280 facilities in 47 technical areas
- 40 square miles of property
- 66% university degrees
- 20% PhDs
- 40% of employees live in Los Alamos

Los Alamos National Laboratory

- 145 R&D 100 Awards
- Budget:
  - 63% Weapons Programs
  - 9% nonproliferation
  - 5% Safeguards and Security
  - 7% Environmental Management
  - 4% DoE Office of Science
  - 12% Other programs

Los Alamos National Laboratory

- Example Research Facilities:
  - Magnet Lab
  - CINT
  - DARHT
  - LANSCE
  - Strategic Computing Complex

Applied Acoustics Lab

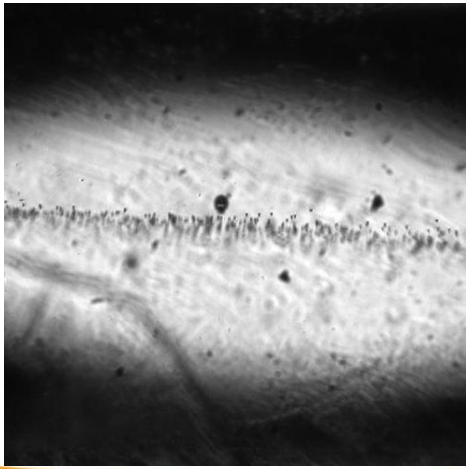
- Group: MPA-11
- 10 Members:
  - 5 Staff Scientists
  - 1 Post Doc
  - 1 Engineering Tech
  - 1 Post Bac
  - 1 Graduate Student
  - 1 Summer Student

Applied Acoustics Lab

- Annual Funding: >$1.5 M
- Typical Funding Sources:
  - DoE
  - LANL
  - Industry
- Example Project Types:
  - Imaging
  - Quality Control
  - Passive Monitoring
  - Noninvasive Characterization of Fluids
  - Material Manipulation

Applied Acoustics Lab

- Past Projects:
  - Noninvasive Chemical Weapon Identification
  - Multiphase Flow Sensor
  - Airborne Particulate Matter Concentrator
  - Acoustic Camera



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SubTER Program

- 4 Pillars:
  - Wellbore Integrity & Drilling Technologies
    - New sensors and materials to ensure integrity
  - Subsurface Stress & Induced Seismicity
    - New approaches to reduce the risks associated with subsurface injections
  - Permeability Manipulation & Fluid Control
    - New methods to enhance, impede, and eliminate fluid flow
  - New Subsurface Signals
    - Transform our ability to characterize subsurface systems

From https://eesa.lbl.gov/subter - LBNL SubTER page

SubTER Program

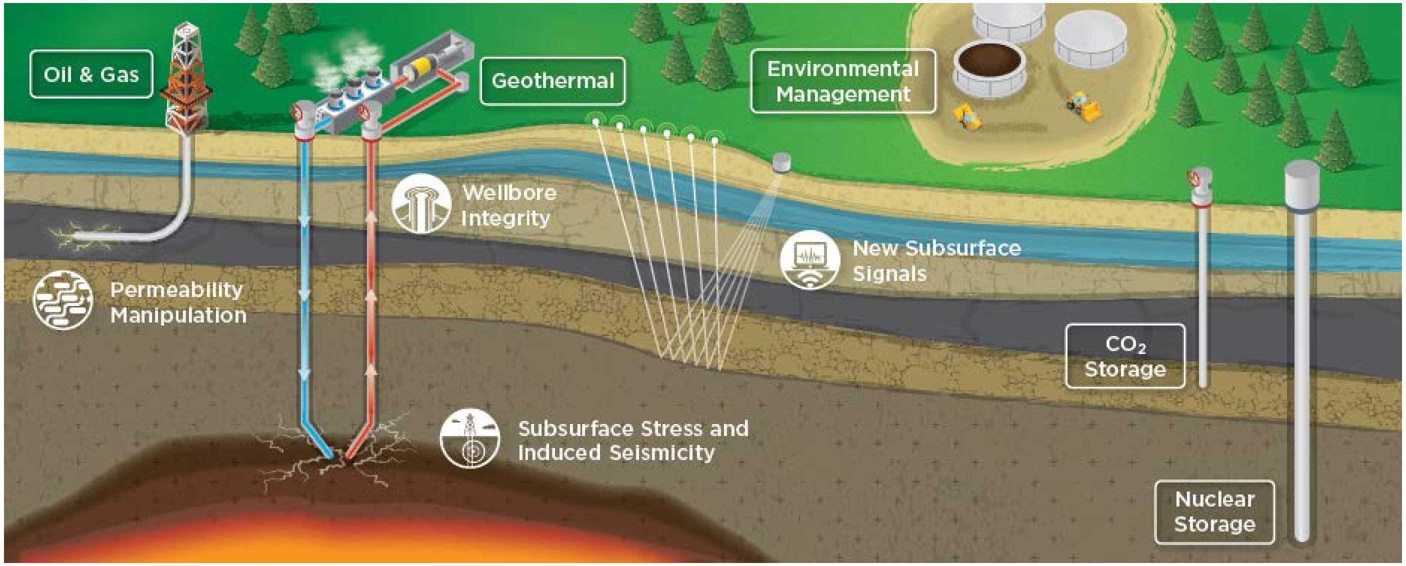
Expected Outcomes:

- **Energy Security**
  - Increase U.S. electrical production from geothermal reservoirs
  - Increase U.S. unconventional oil and natural gas
- **Protect the Environment**
  - President's Climate Action Plan: Safely store CO_2 to meet GHG emissions reduction targets
  - Safe storage/disposal of nuclear waste
  - Reduced risk of induced seismicity
  - Protect drinking water resources
- **Economical and Social Benefits**
  - Retain U.S. subsurface leadership
  - Increase revenues to Federal, State, and local governments
  - Increased public confidence in subsurface energy sector

From https://eesa.lbl.gov/subter - LBNL SubTER page

SubTER Program

- Our fit: wellbore integrity and drilling technology
- Benefits:
  - Safely sequester CO_2 on a large scale
  - Establish feasibility of deep borehole disposal
  - Protect public safety and the environment



Main objective: develop a high-resolution 3D imaging system for improved wellbore diagnostics and integrity assessment

- Challenges addressed: High-resolution imaging of interfaces and shallow formation/ detection of small cracks and features
- Costs – Similar to existing wireline tools or better
- Performance – Longer range, better resolution
- Applications – wellbore integrity assessment/ borehole impact on formation
- Markets – Oil & gas, geothermal, CO_2 sequestration
- Innovative aspects: low frequency, collimated beam.
  - Combination of a unique source with advanced image processing
  - An approach that can be deployed to characterize foamed cements in-situ

    ⟶ identify acoustic-based metrics from comparison with CT scans

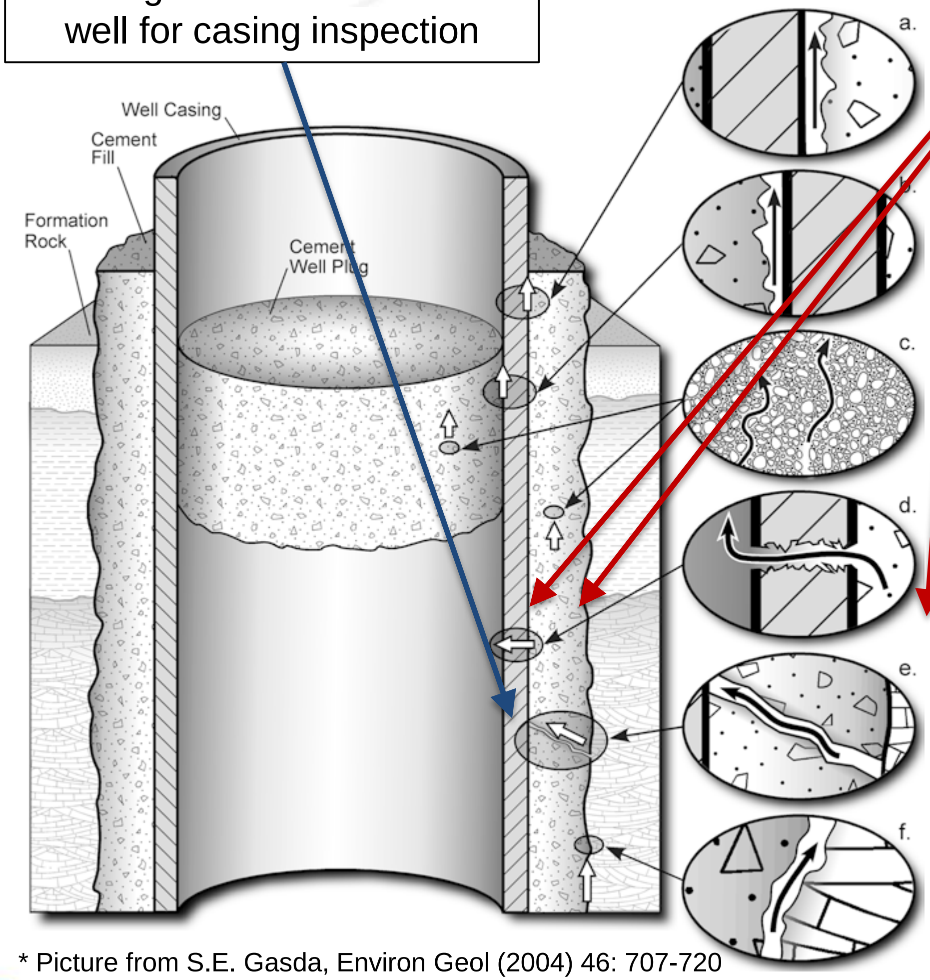
Scope of Work

The Problem:

Defects/fracture detection beyond casing with high resolution. No current techniques.

Existing ultrasonic tools work well for casing inspection

We plan to extend applicability to: (1) casing-cement interface, (2) cement-formation interface, and (3) out in the formation (up to ~ 3 meters).



* Picture from S.E. Gasda, Environ Geol (2004) 46: 707-720

Comparison of existing techniques and the present approach

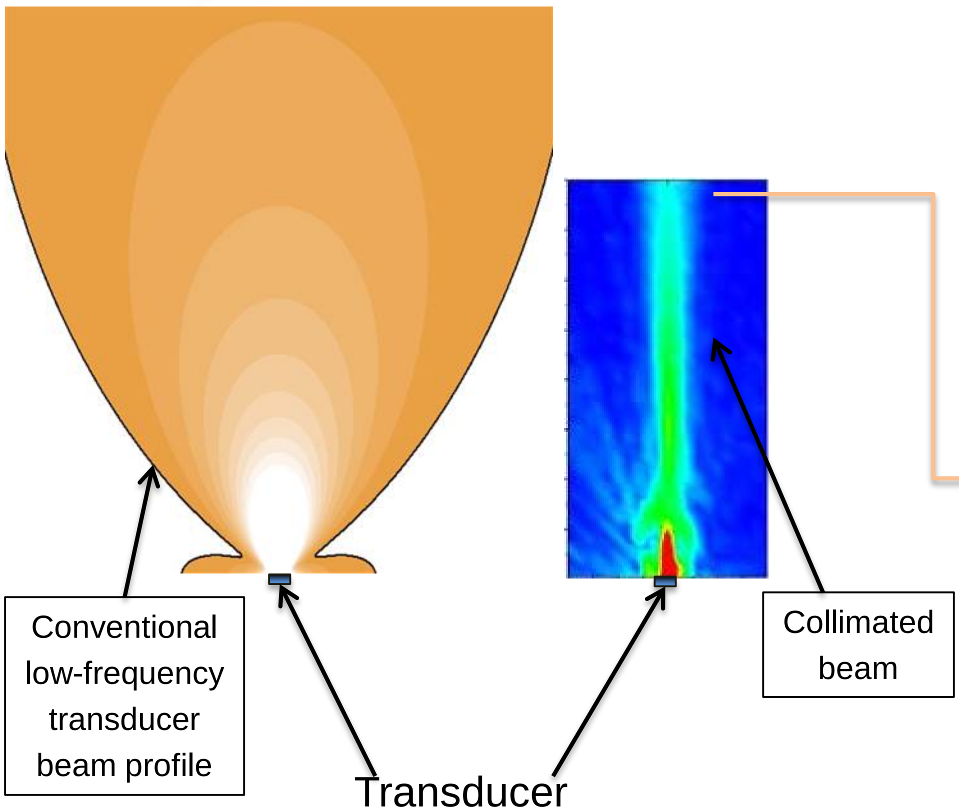
Method	Frequency (kHz)	Range (m)	Resolution (mm)
Standard borehole sonic probe, e.g. BARS (Borehole Acoustic Reflection Survey)	0.3-8	15	~ 300
Present approach	10-150	~ 3	~ 5
Ultrasonic probe, e.g. UBI (Ultrasonic Borehole Imager)	>250	casing	4-5

Scope of Work

The Proposed Solution:

Novel technique that fills this technology gap.

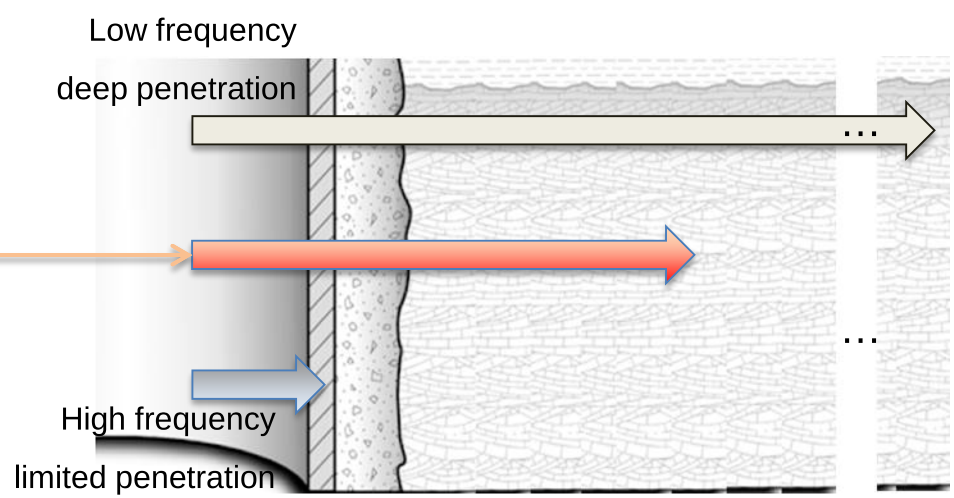
1. Collimated beam for increased resolution



2. Low frequency for deeper penetration

$$Attenuation \sim f^{n}$$

f = frequency, n = 1-2



Scope of Work

Long-term objectives:

Develop a high-resolution 3D imaging system, based on:

- unique acoustic source (low frequency, highly collimated, broad-band: 10-150 kHz, high power)
- advanced image processing.

Investigate effectiveness of next generation wellbore completion technology such as foamed cements.

Phase 1

Feasibility study

- Existing technology
- Define metrics
- Industry/maturation

LANL/ NETL/ ORNL/ SNL

Phase 2

Evaluate method on more complex wellbore environments

- Make cement/seal — NETL
- Characterize w/CT — NETL
- Test Acoustics — LANL
- Simulated well tests — SNL/LANL
- Refine 3D processing — LANL/ORNL

Phase 3

Extend method beyond wellbore

- Enhanced sensors — LANL
- Refine algorithm — ORNL/LANL
- Testing of new sensors — SNL/LANL
- Adapt sensors for foamed cements — NETL/LANL

Phase 4

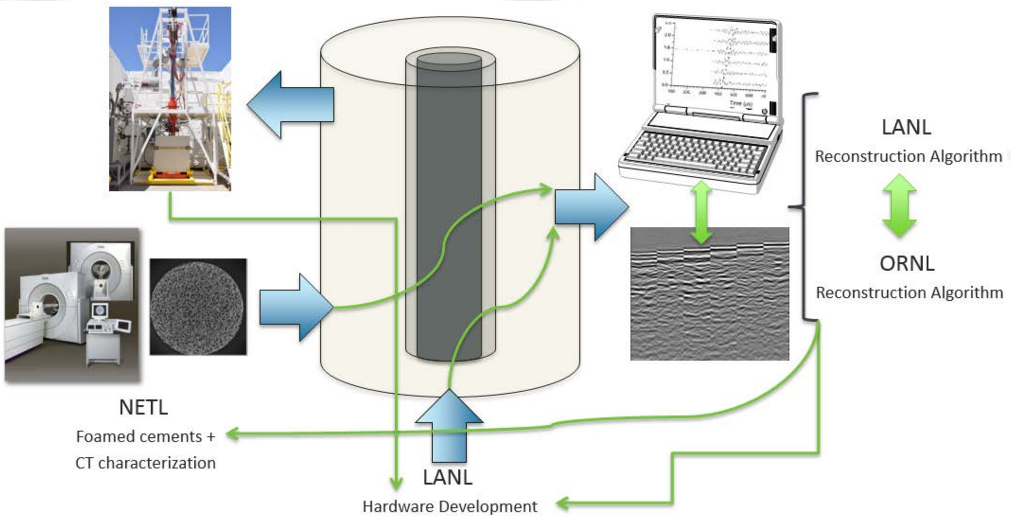
Technology Development and Verification

- Develop prototype — LANL
- Refine algorithm — ORNL/LANL
- Initiate tests in real wells — SNL/NETL/ LANL

Outcome:

- improved imaging resolution around the borehole
- extended investigation range - beyond the wellbore casing

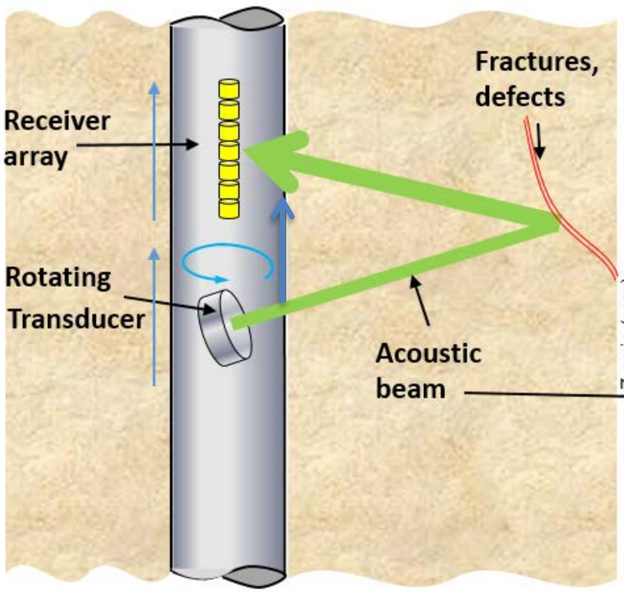
Scope of Work



- Multi-lab project:
  - Develop acoustic source and imaging system (LANL)
    - → Develop imaging system and perform experiments for defects detection
  - Explore different *image processing* approaches (LANL + ORNL).
    - →The best choice (or complementary use) will be selected for future experiments
  - Perform experiments in more realistic boreholes (LANL + SNL)
    - → Incorporate data from realistic borehole and compare resolution with lab experiments
  - Investigate acoustic metrics for *foamed cements* (LANL + NETL).
    - → Incorporate new metrics for wellbores in the field

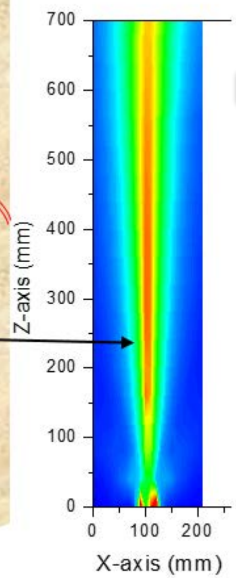
Scientific/Technical Approach

Schematic representation of the 3D imaging system:

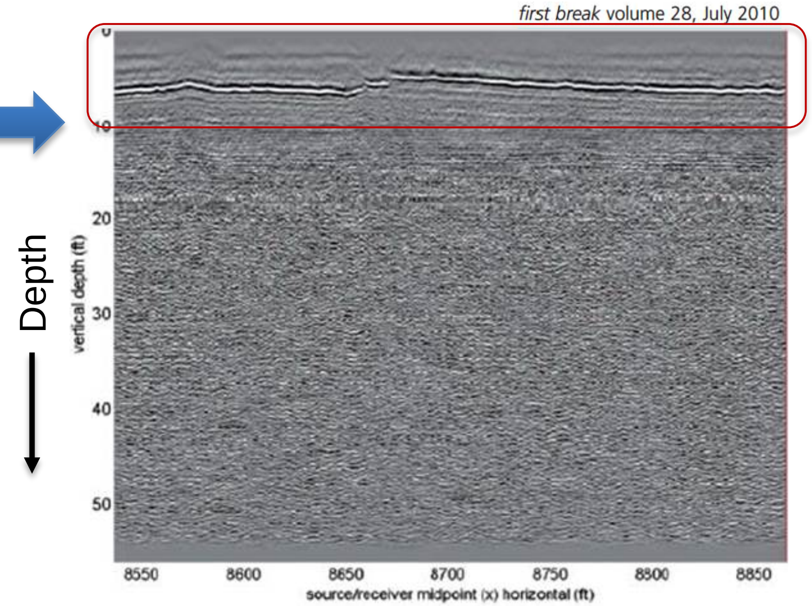


360 degree imaging

Low frequency
Collimated beam
(10-150 kHz)

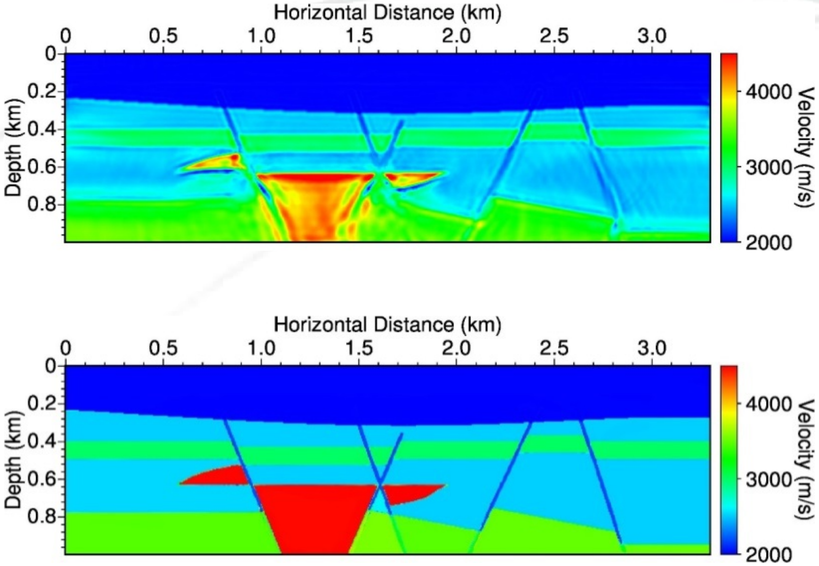


No side-lobes

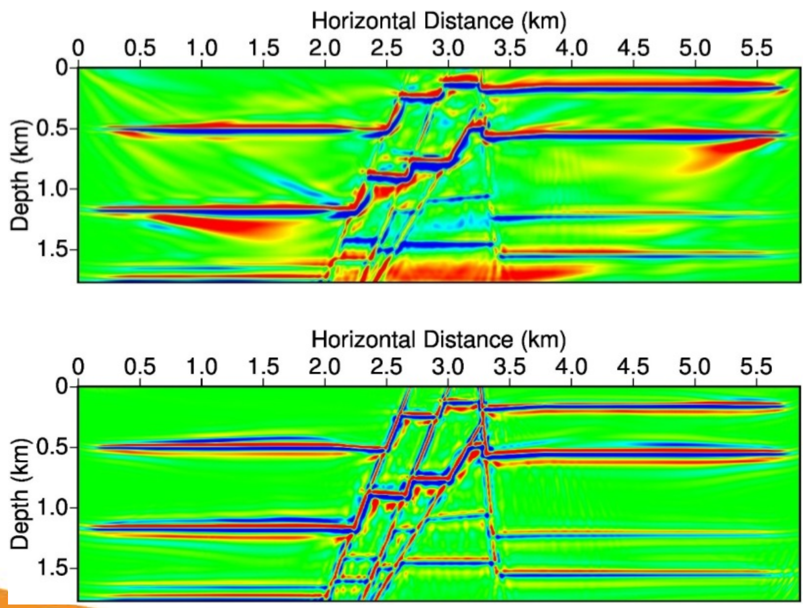


Scientific/Technical Approach

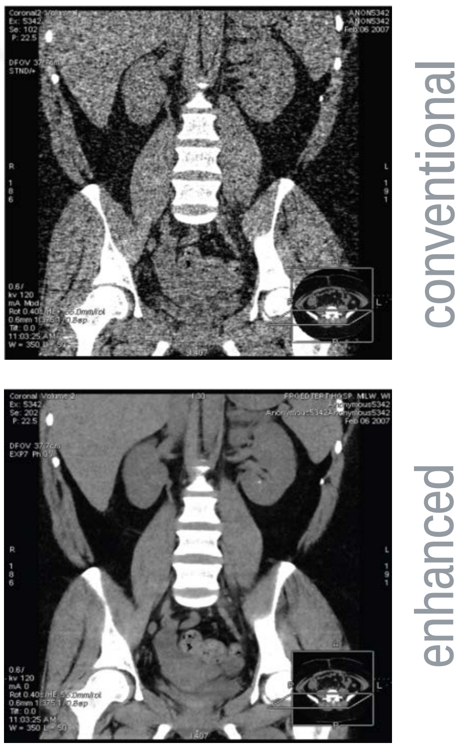
Advanced Image Processing Techniques



LANL Elastic-Waveform Inversion



LANL Least-Squares Reverse-Time Migration



ORNL Model-Based Iterative Reconstruction

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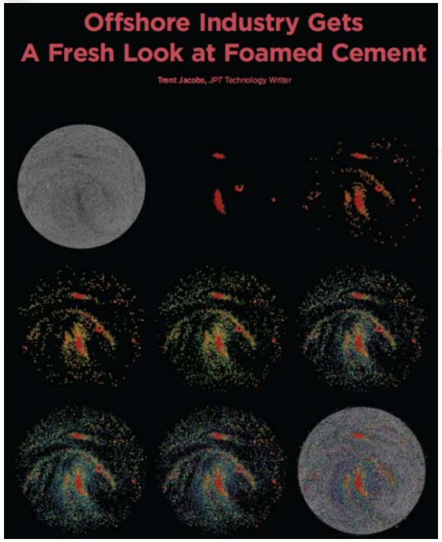
Scientific/Technical Approach

- **Foamed cements (w/ NETL)**
  - limited information on foamed cement behavior at conditions specific to wellbores exists at present
  - conventional methods have difficulty detecting foamed cement due to low impedance contrast.



* From JPT, vol . 67, no. 1, Jan 2015

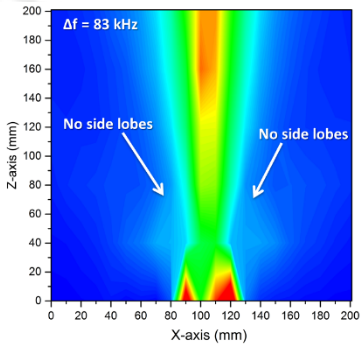
Acoustic (*LANL*) ←→ CT (*NETL*)

Acoustic characterization: sound speed, attenuation, acoustic nonlinearity, elastic moduli

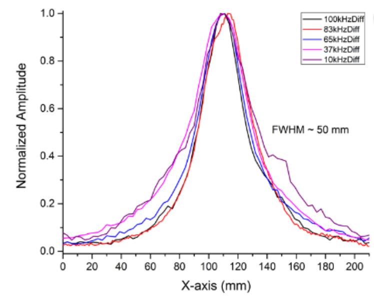
- **Realistic environments (w/ Sandia)**
  - Perform imaging experiments in more realistic simulated wellbore environments
  - Granite blocks with induced and simulated defects

Scientific/Technical Approach
Acoustic Source

- **Parametric Acoustic Source**:
  - Low frequency (10-150 kHz)
  - Large bandwidth (140 kHz)
  - Frequency-independent beam width
  - No side lobes
  - Beam divergence < 6 degrees



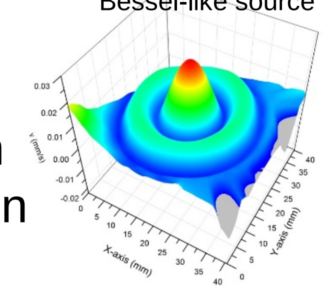
83 kHz difference frequency beam profile in H_2O



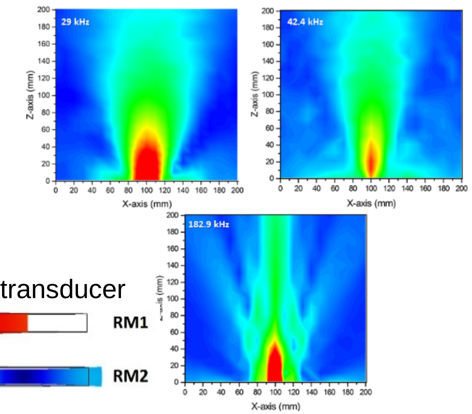
Scans of beam widths at 110 mm from transmitter in H_2O

- **Bessel-like Acoustic Source**:
  - Low frequency (10-150 kHz)
  - Large bandwidth (140 kHz)
  - Frequency-independent beam width
  - Limited diffraction during propagation
  - Reduced side lobes

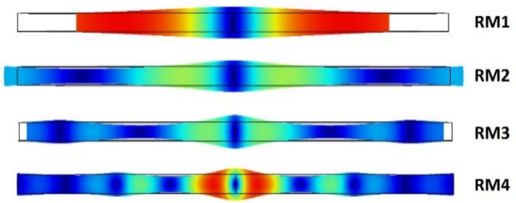
Transducer surface profile of a Bessel-like source



Examples for low-frequency beam profiles in H2O for a Bessel-like source



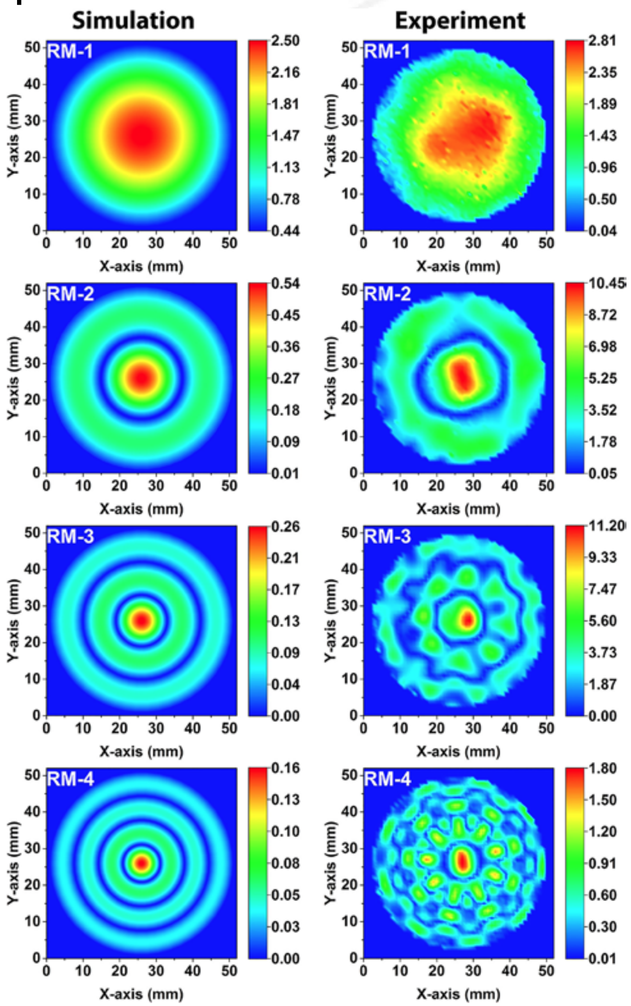
Radial modes of a Bessel-like transducer



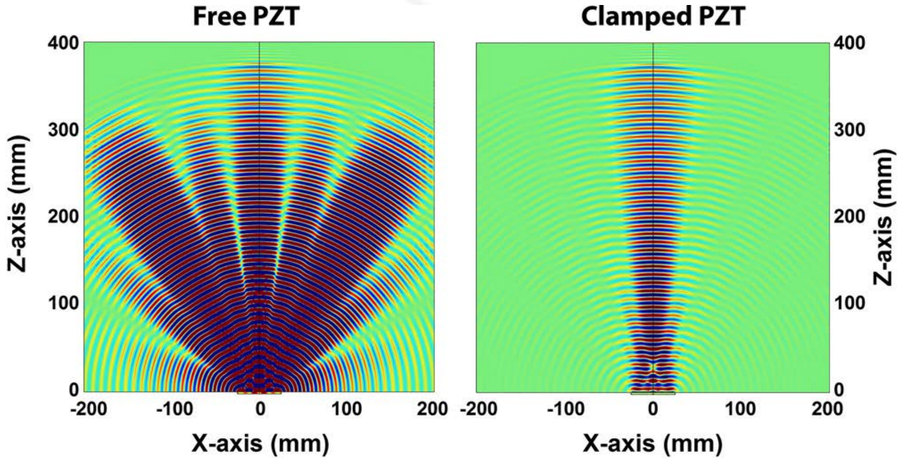
- **Compact Parametric Acoustic Source**:
  - Very compact source; can be fitted in boreholes 1-2 in ID
  - IP process underway

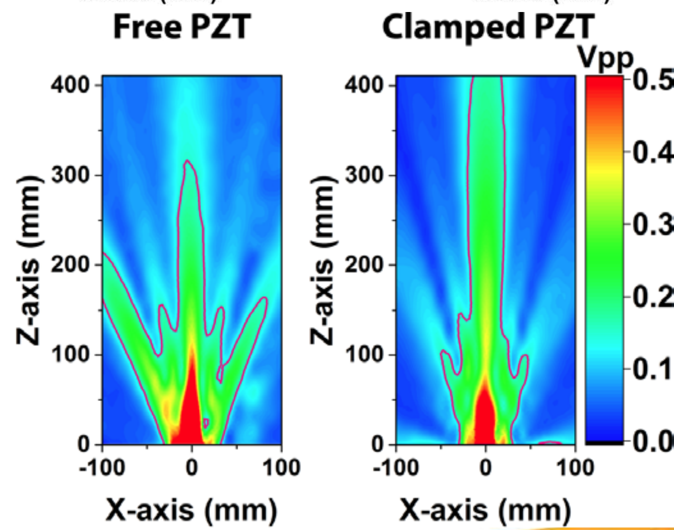
Scientific/Technical Approach
Bessel-like Acoustic Source

First four radial modes of a piezoelectric disc transducer



Beam profile in water for the 3rd radial mode RM-3; free transducer (left) and clamped transducer (right)

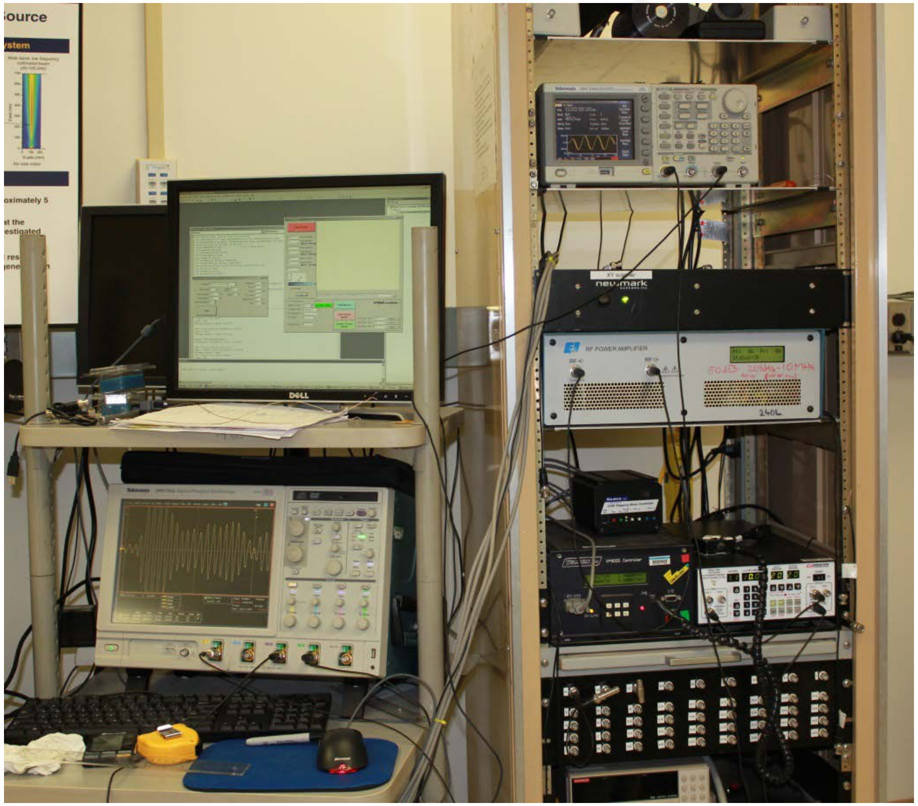




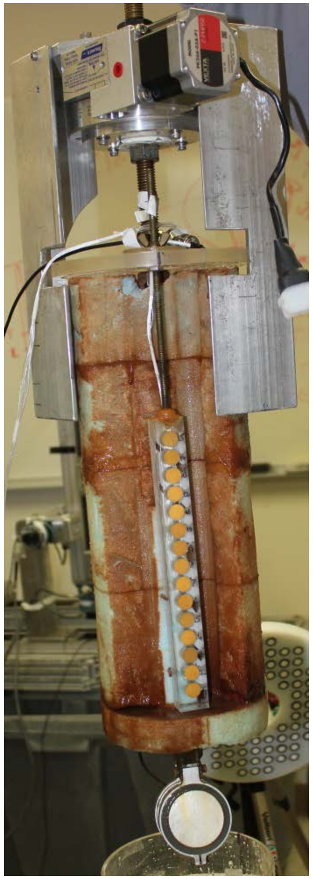
Scientific/Technical Approach
Original Measurement system

Simulated borehole:
metal casing embedded in cement.

Electronics



Acoustic source
+
receivers array



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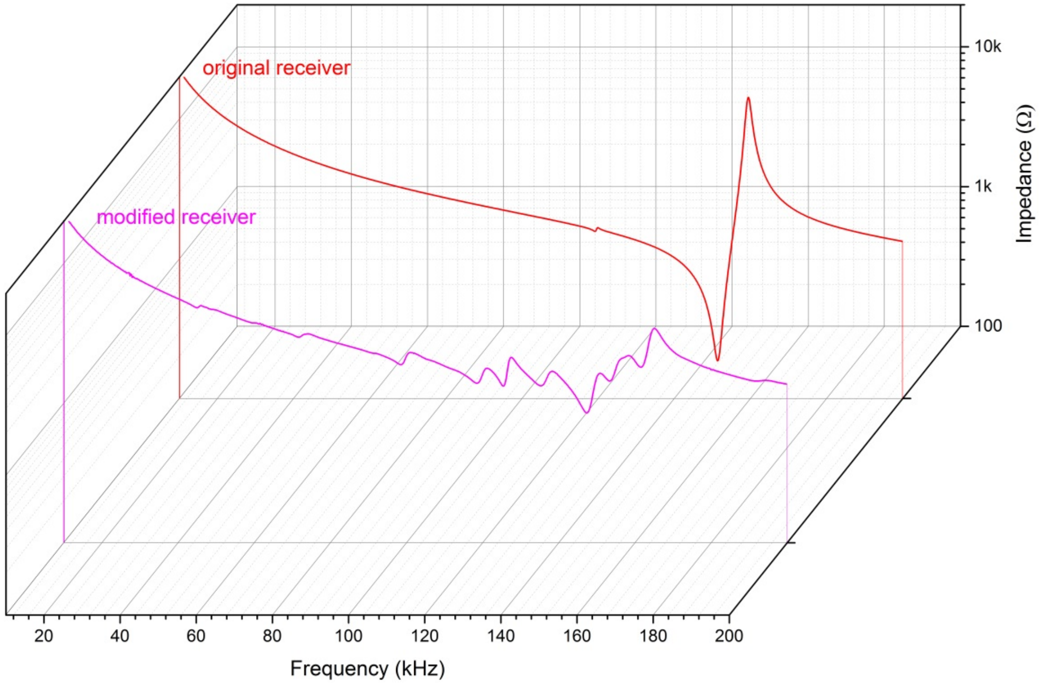
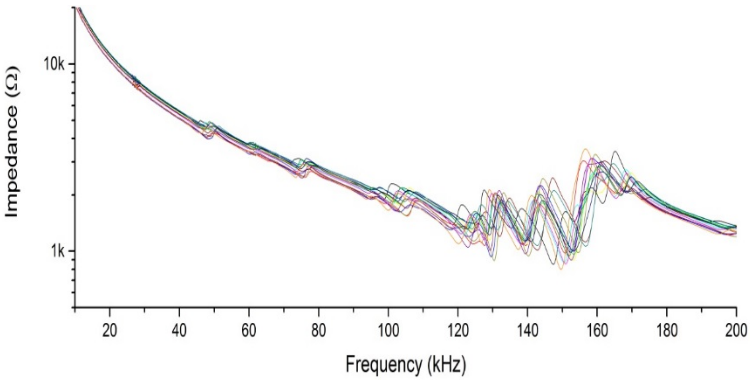
Scientific/Technical Approach
Original Measurement system

- 15 Piezo-electric transducers (PZT) mounted vertically
- Central frequency 500 kHz

- Backed with tungsten and epoxy
- Backing improves frequency bandwidth
- Transducers are now more sensitive to range of interest, 10-200 kHz



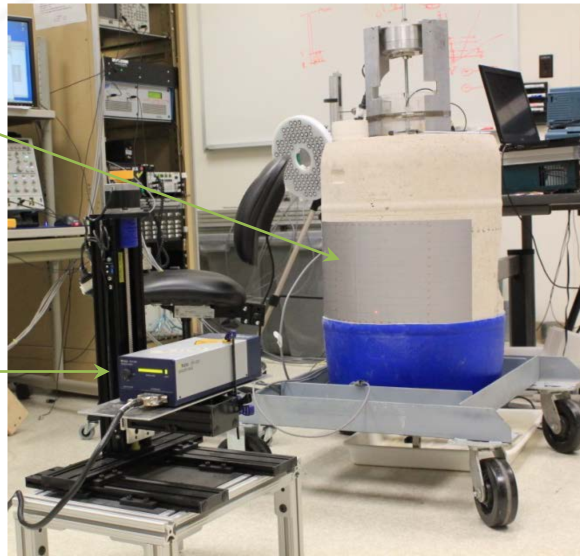


Scientific/Technical Approach
Beam pattern through concrete

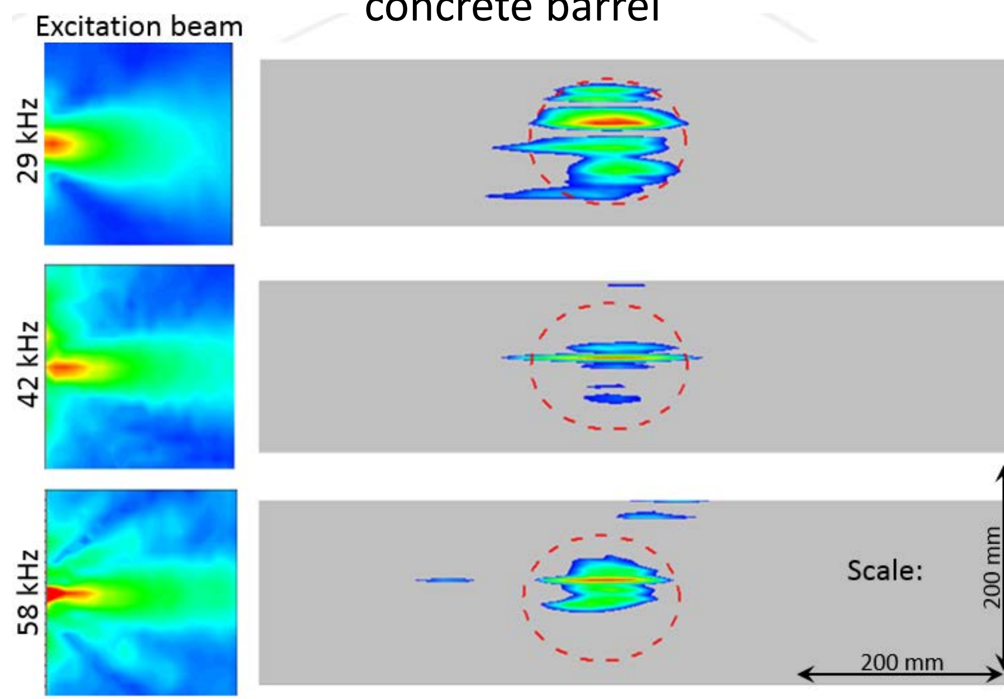
Experimental setup for beam pattern determination after propagation through concrete

Reflective Tape / Concrete Barrel

Laser Doppler Vibrometer

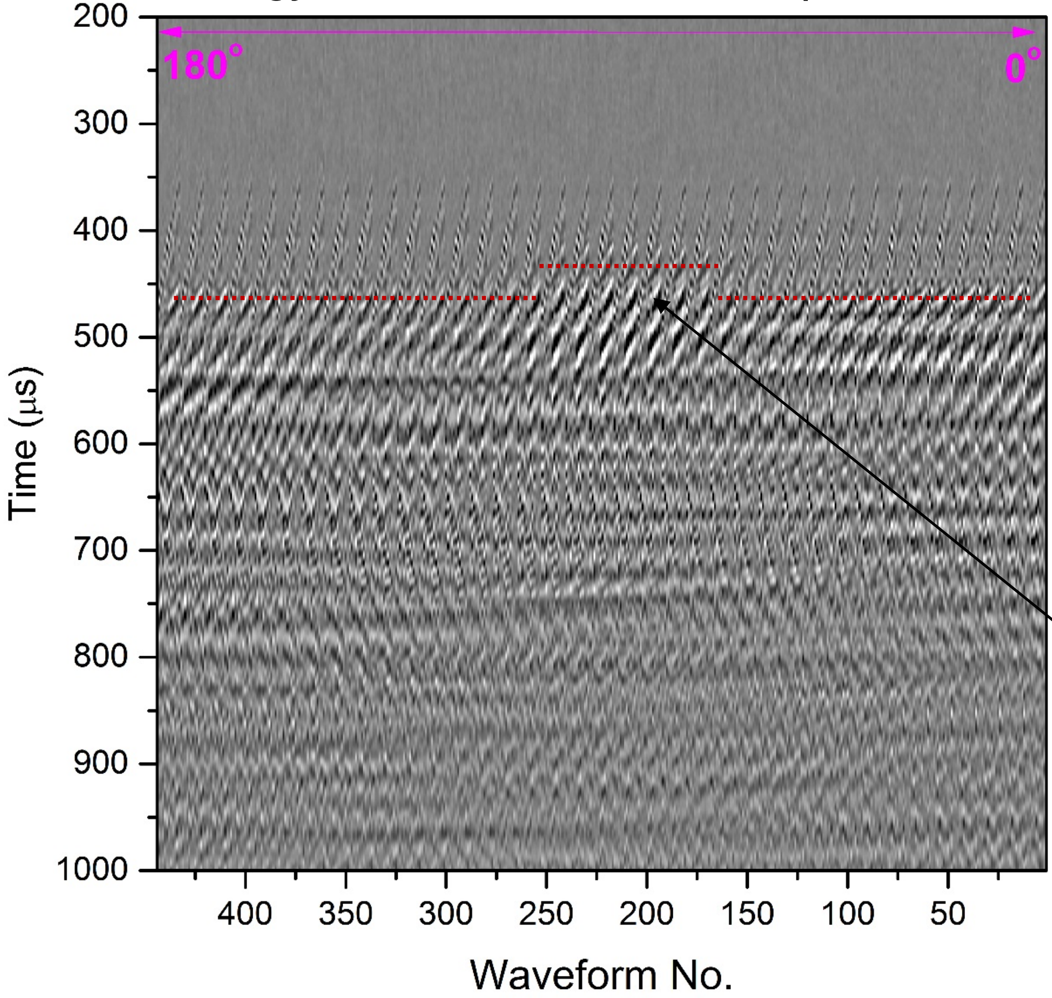


- 6 dB power beam pattern on the face of the concrete barrel



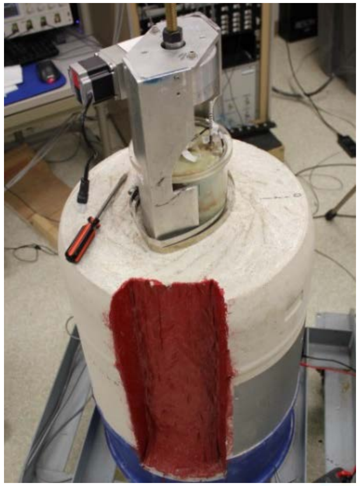
Scientific/Technical Approach
Imaging with parametric source

Open borehole configuration (plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation



Excitation:
10-150 kHz Gaussian pulse
Azimuthal data collected every 5 deg, for a 180 deg span.

Groove location

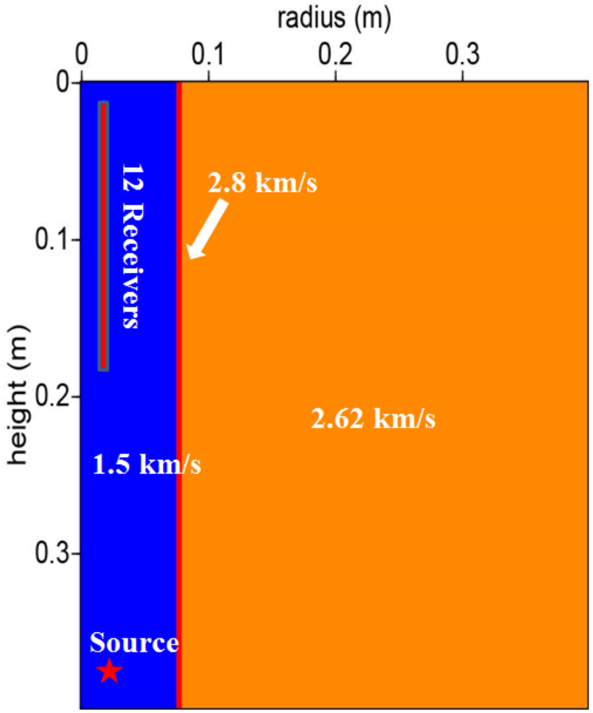


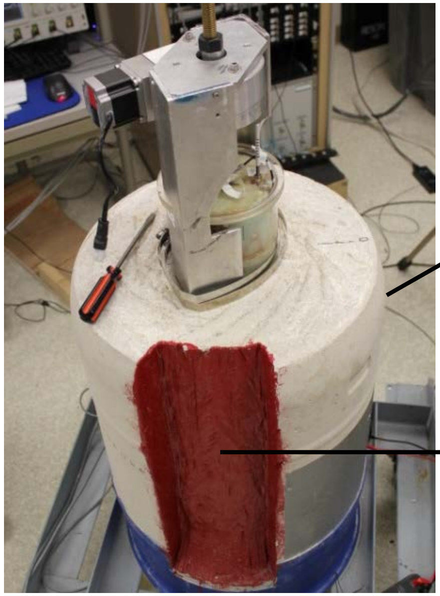
Cement OD: 477 mm
Cement ID:152 mm
Plexiglas pipe ID: 146 mm
plexiglas pipe thickness: 3 mm
Groove depth: 50 mm

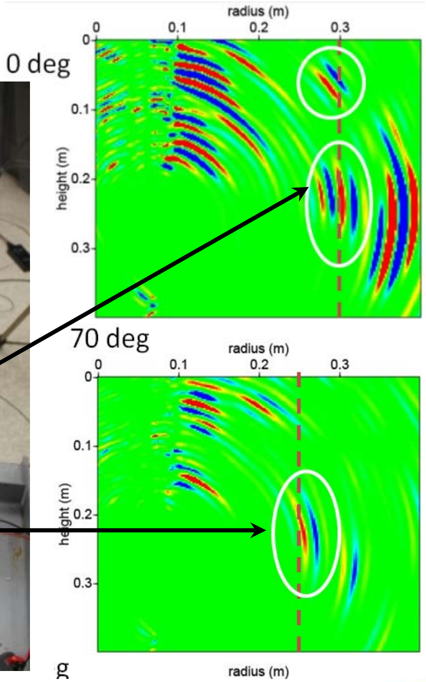
Scientific/Technical Approach
LANL image processing

Open borehole configuration (plexiglas-lined cement barrel)
Least-squares reverse-time migration

Excitation:
10-150 kHz Gaussian pulse
Azimuthal data collected every 5 deg, for a 180 deg span.







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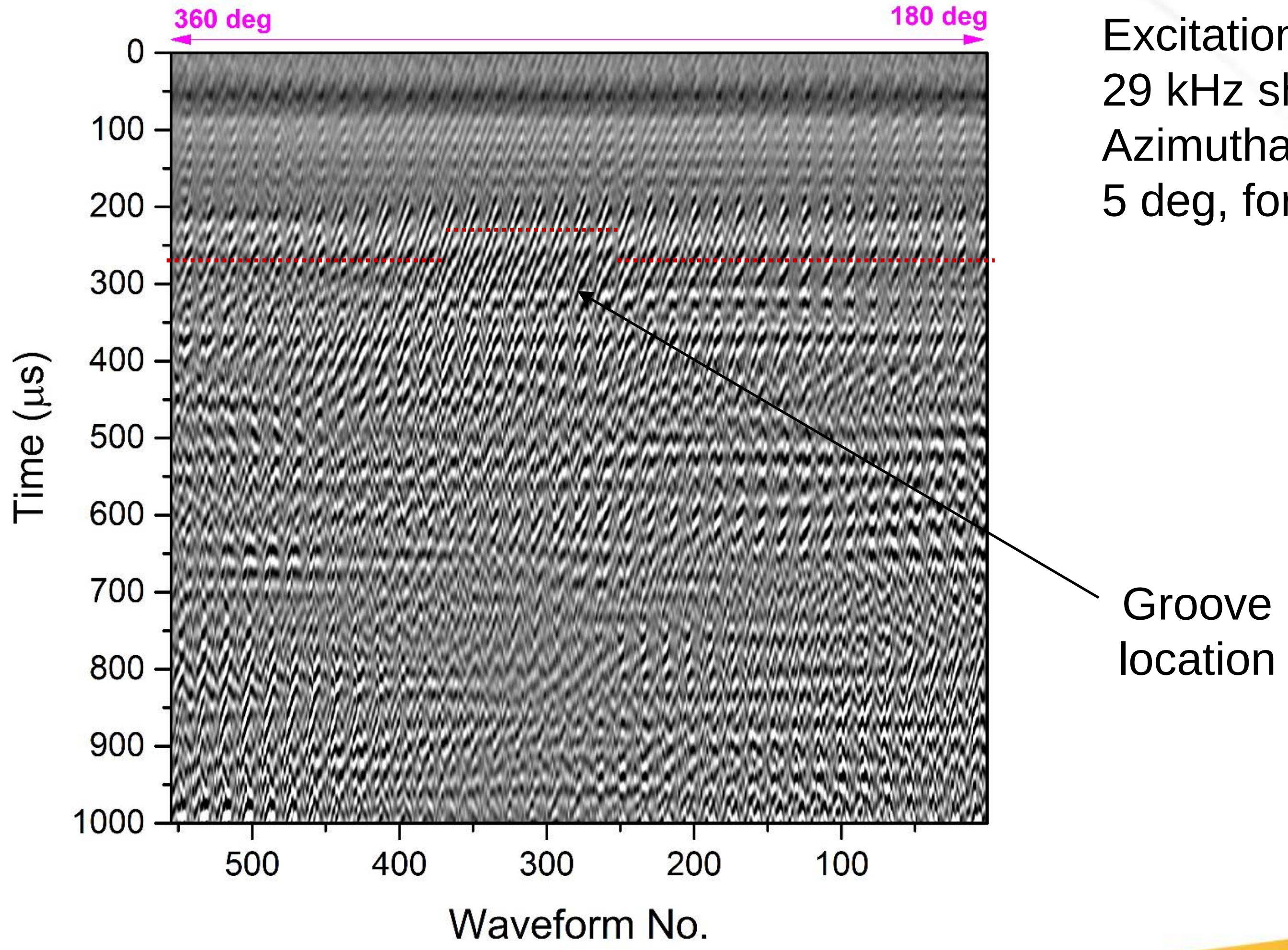
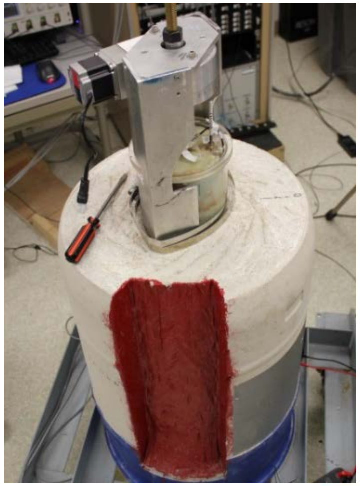
Scientific/Technical Approach
Imaging with Bessel-like source

Open borehole configuration (Plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation



Excitation:
29 kHz shaped pulse
Azimuthal data collected every 5 deg, for a 180 deg span.



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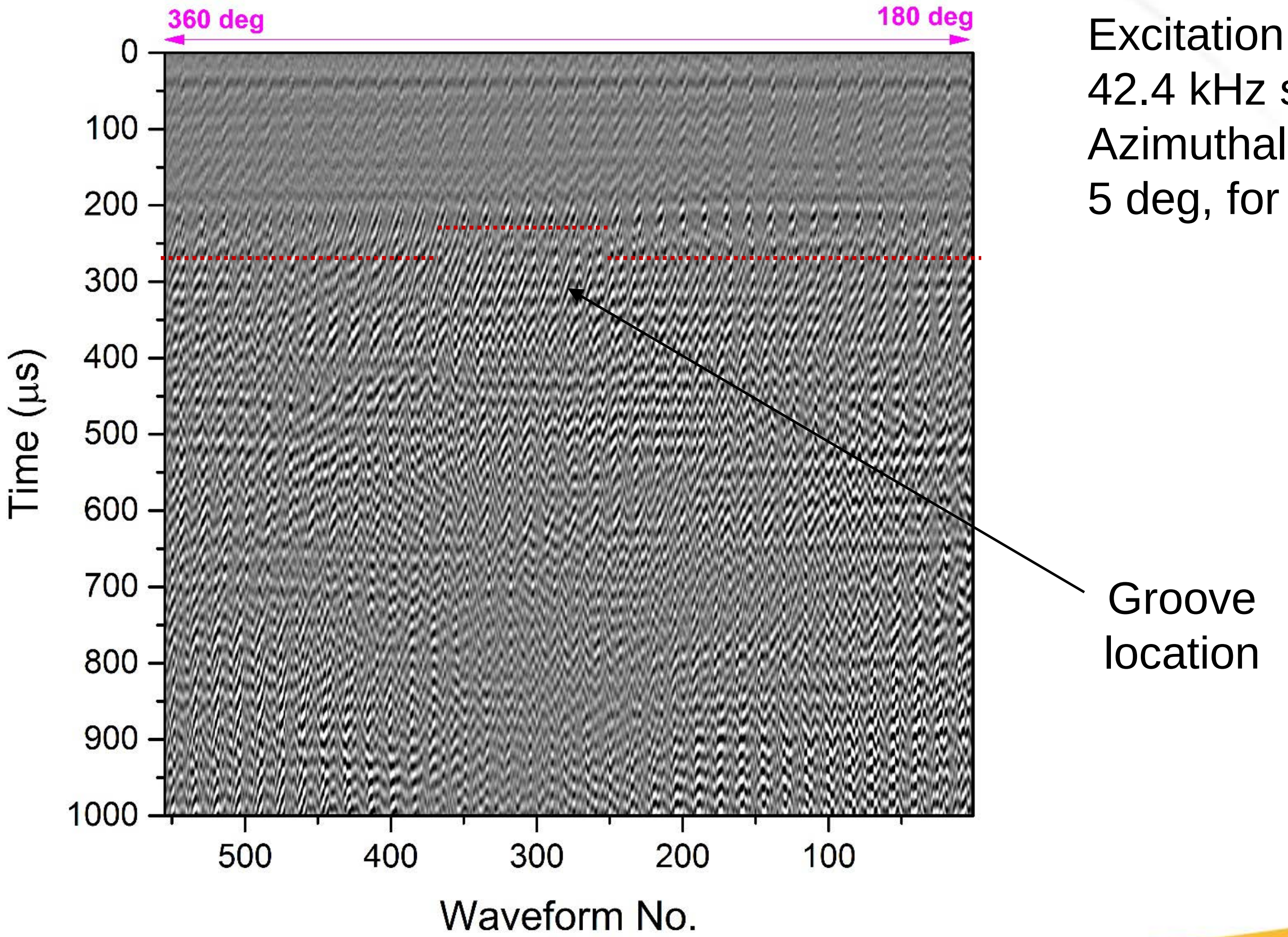
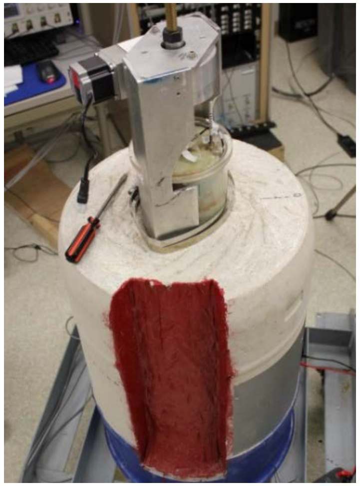
Scientific/Technical Approach
Imaging with Bessel-like source

Open borehole configuration (Plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation

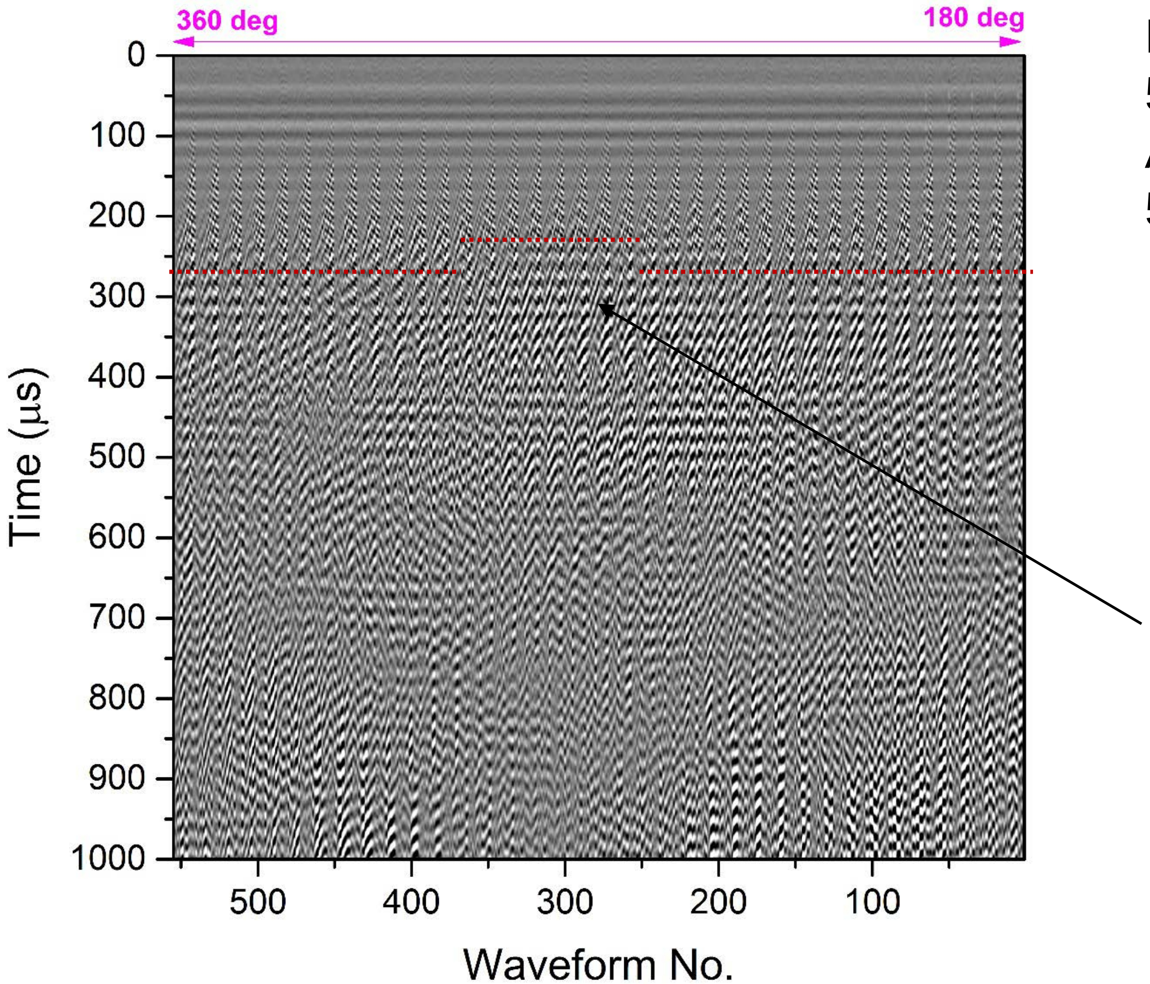


Excitation:
42.4 kHz shaped pulse
Azimuthal data collected every 5 deg, for a 180 deg span.

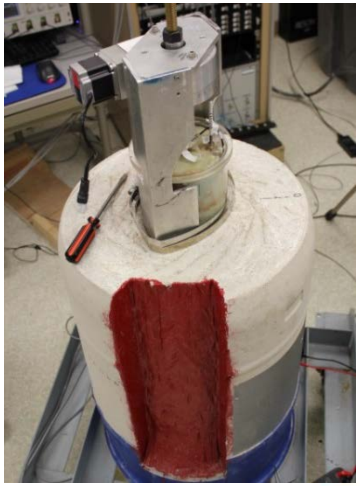


Scientific/Technical Approach
Imaging with Bessel-like source

Open borehole configuration (Plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation

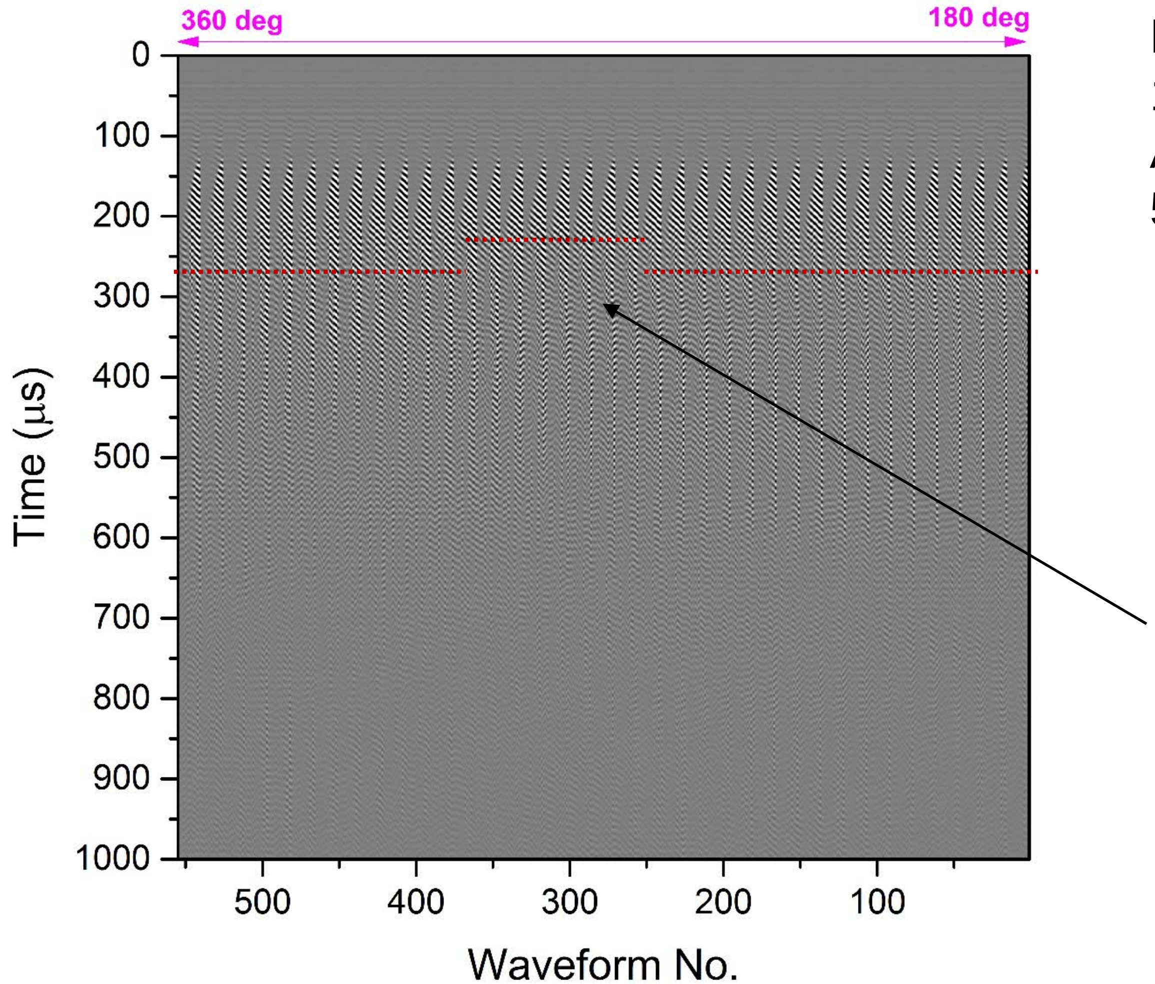


Excitation:
58 kHz shaped pulse
Azimuthal data collected every 5 deg, for a 180 deg span.

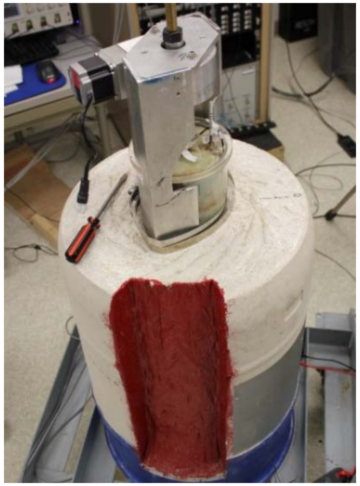


Scientific/Technical Approach
Imaging with Bessel-like source

Open borehole configuration (Plexiglas-lined cement barrel)
Reflection seismology – Common azimuth representation

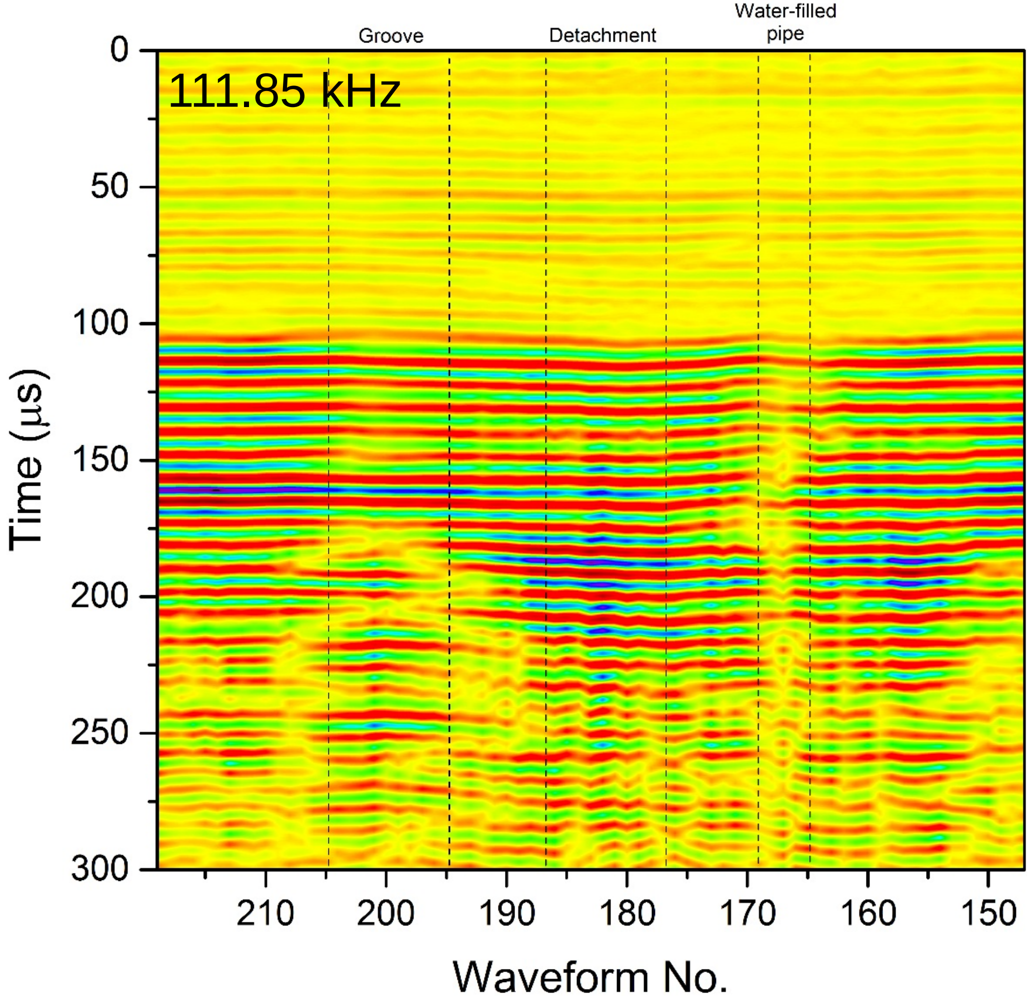


Excitation:
111.85 kHz shaped pulse
Azimuthal data collected every 5 deg, for a 180 deg span.

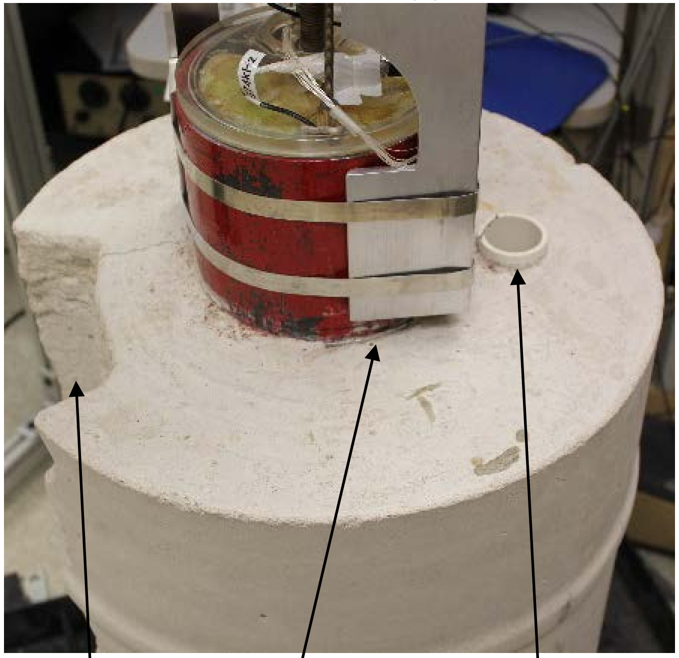


Scientific/Technical Approach
Defects detection – Bessel-like Source

Cased borehole configuration (Steel-lined cement barrel)
Reflection seismology – Common receiver representation



Cement OD: 460 mm
Cement ID:170 mm
Steel pipe ID: 148 mm
Steel pipe thickness: 10 mm
Groove depth: 50 mm
Plastic pipe location: 25 mm

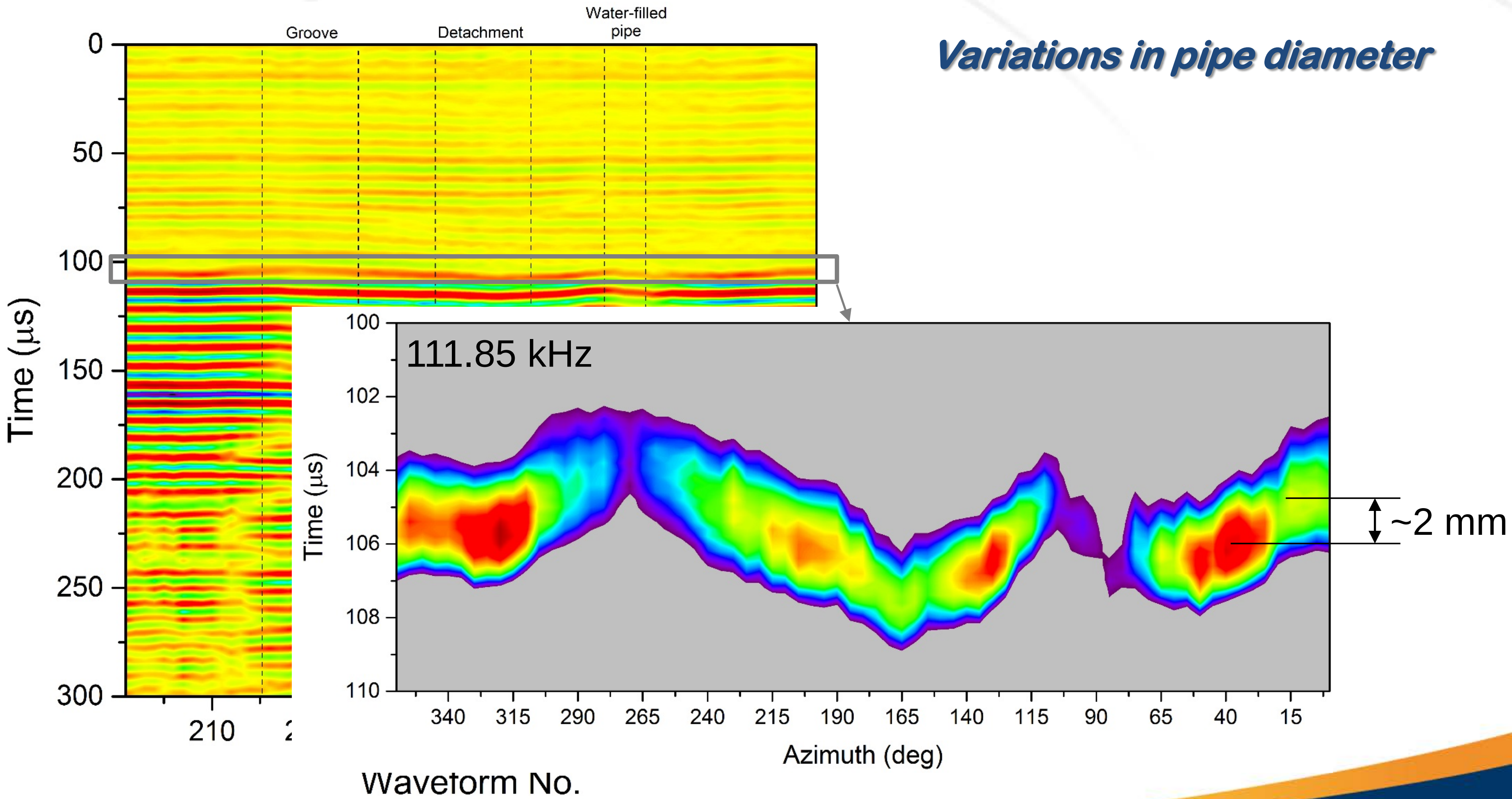


Groove
Detachment
Water-filled pipe

Scientific/Technical Approach
Defects detection – Bessel-like Source

Steel casing barrel – Bessel-like Source

Variations in pipe diameter



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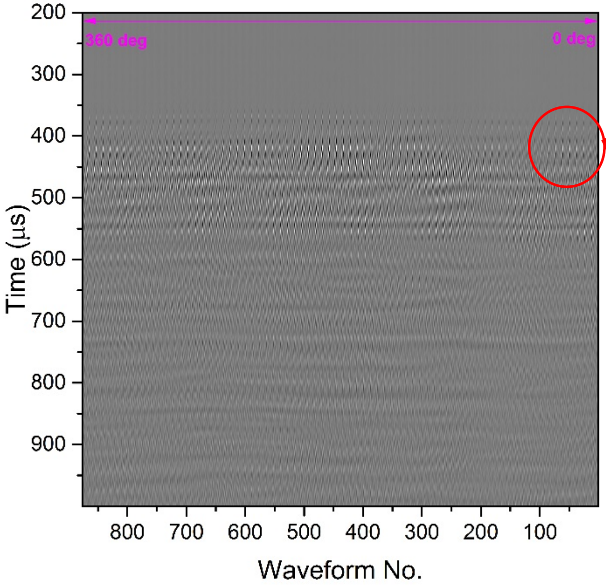
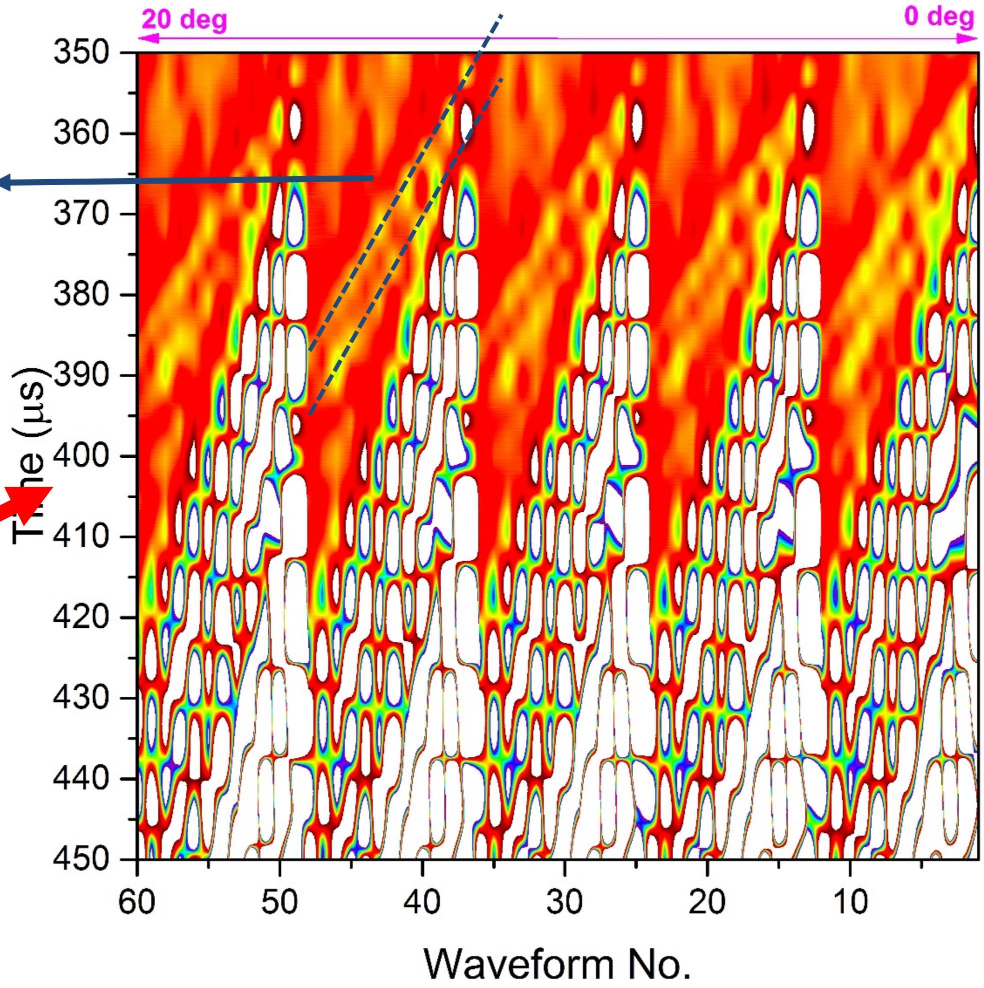
Scientific/Technical Approach
Resolution determination

Steel casing barrel – Parametric Source

Calculations:
- Sound speed: ~5.8 km/s
- Thickness: ~10 mm

→ ***Steel***





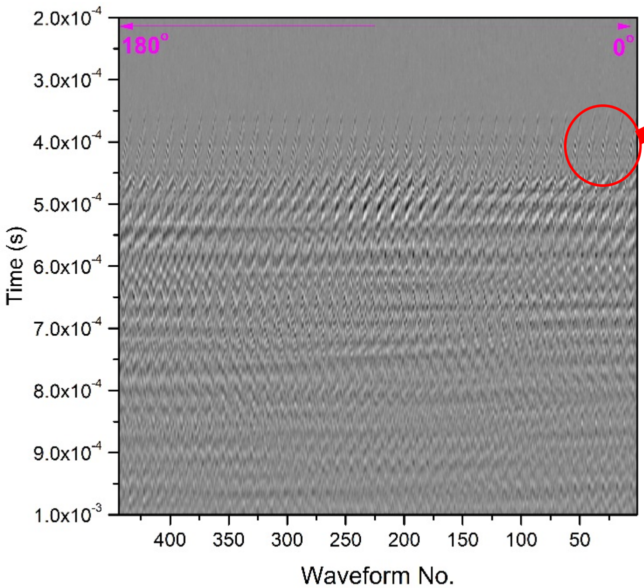
Scientific/Technical Approach
Resolution determination

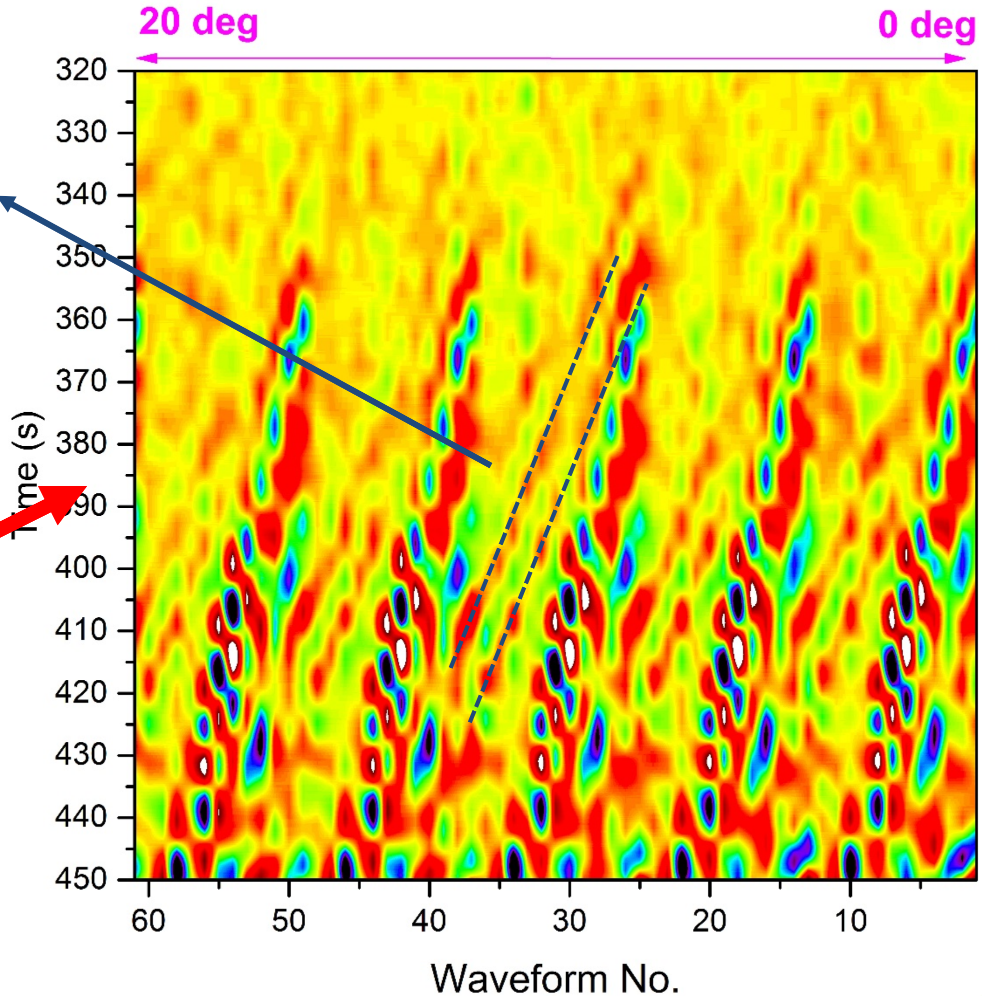
Plexiglas casing barrel – Parametric Source

Calculations:

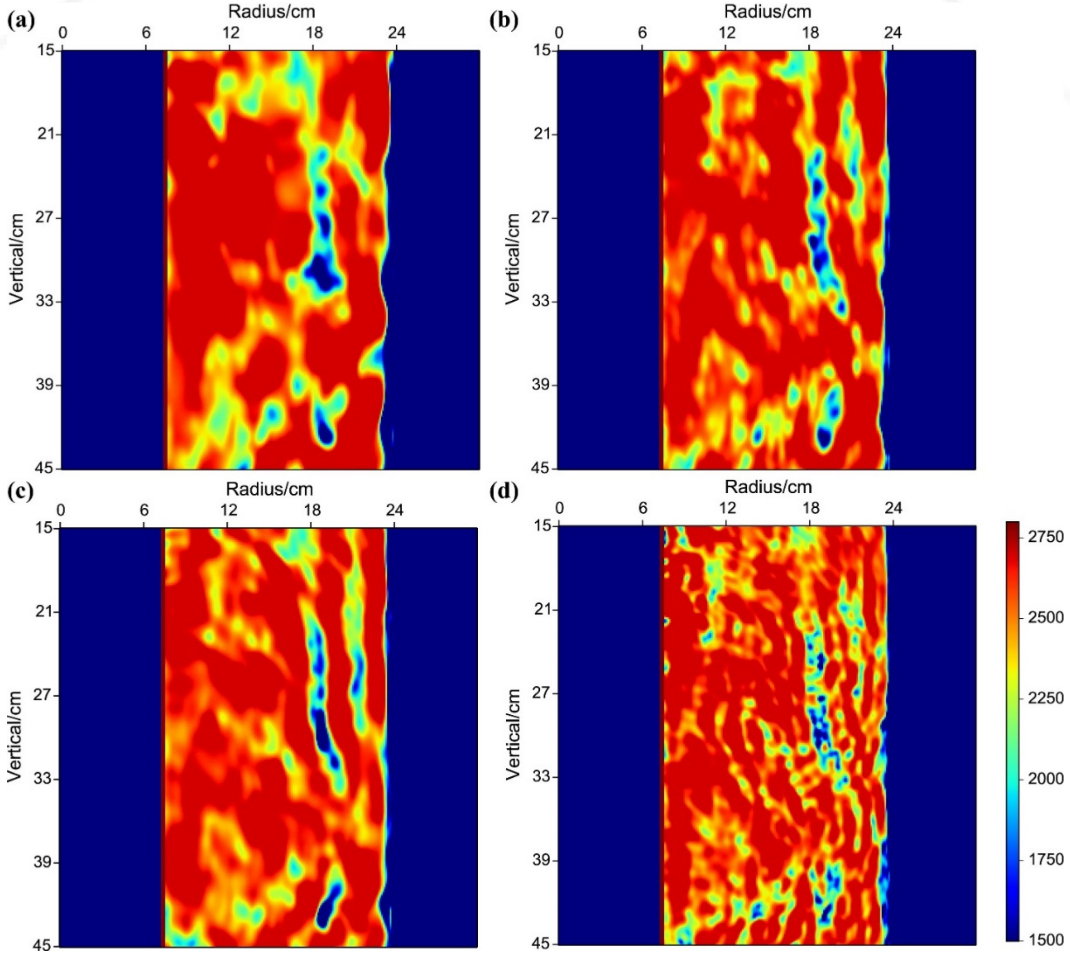
- Sound speed: ~2.8 km/s
- Thickness: ~3 mm

→ ***plexiglas***





Velocity model for the long-radius profile from acoustic inversion using (a) 29 kHz data, (b) 42.4 kHz data, (c) 58 kHz data, and (d) 111.85 kHz data.



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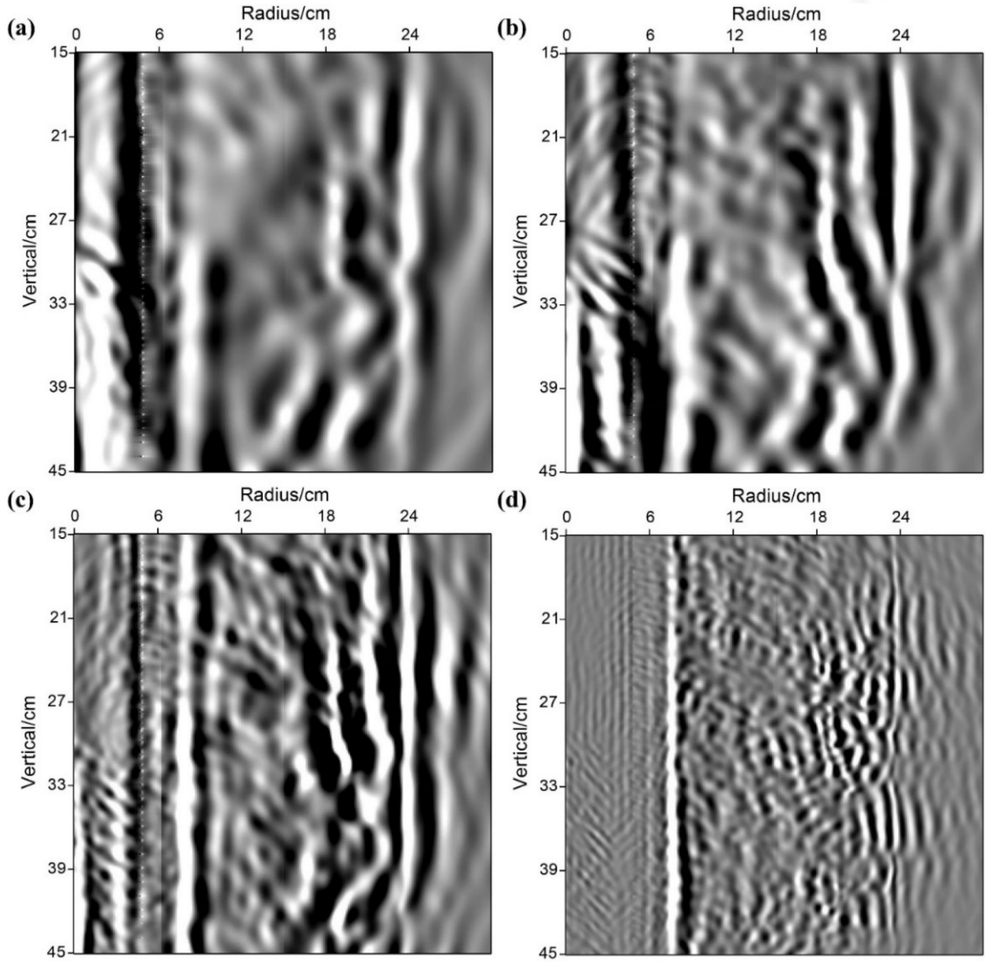
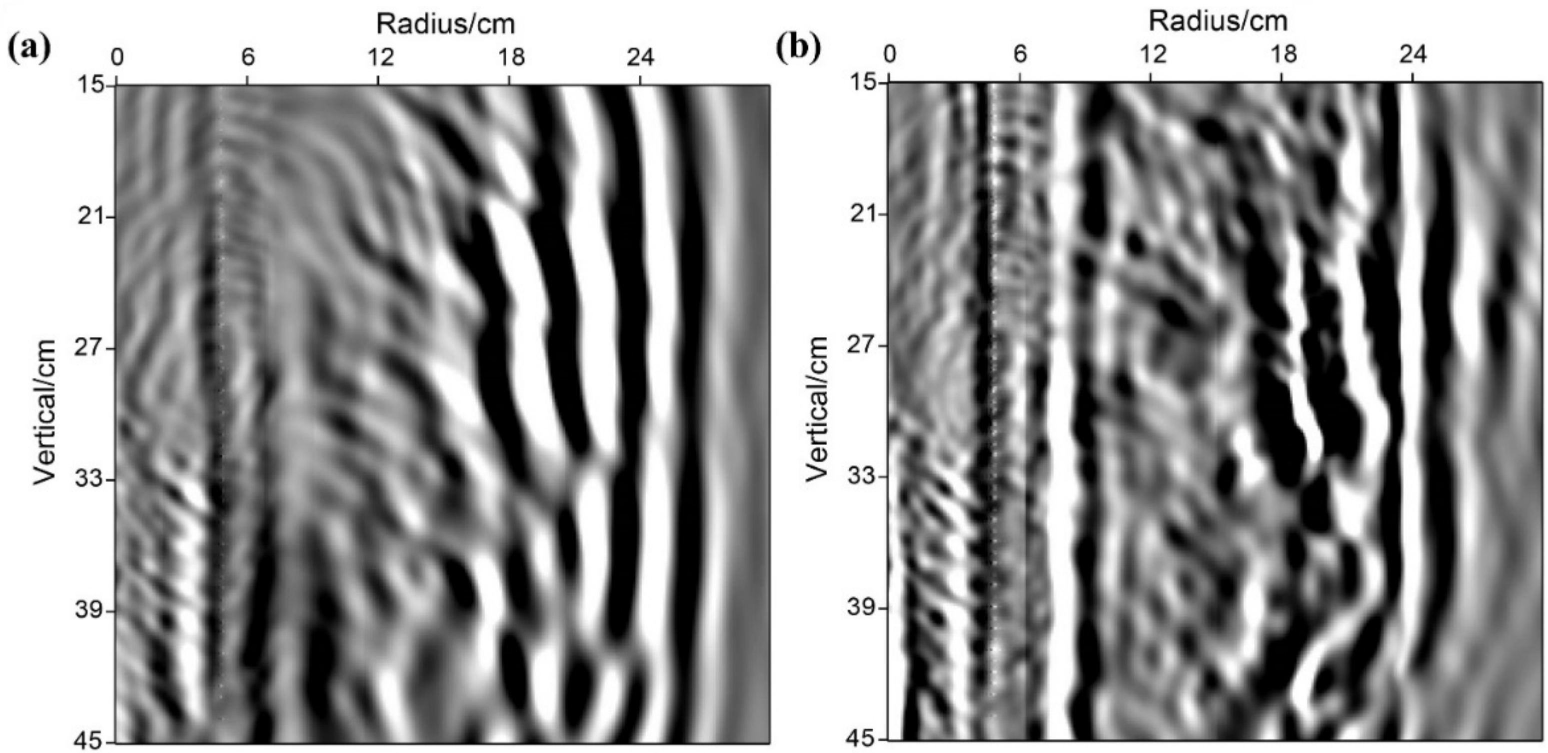
LSRTM imaging for the long-radius profile using (a) 29 kHz data, (b) 42.4 kHz data, (c) 58 kHz data, and (d) 111.85 kHz data.

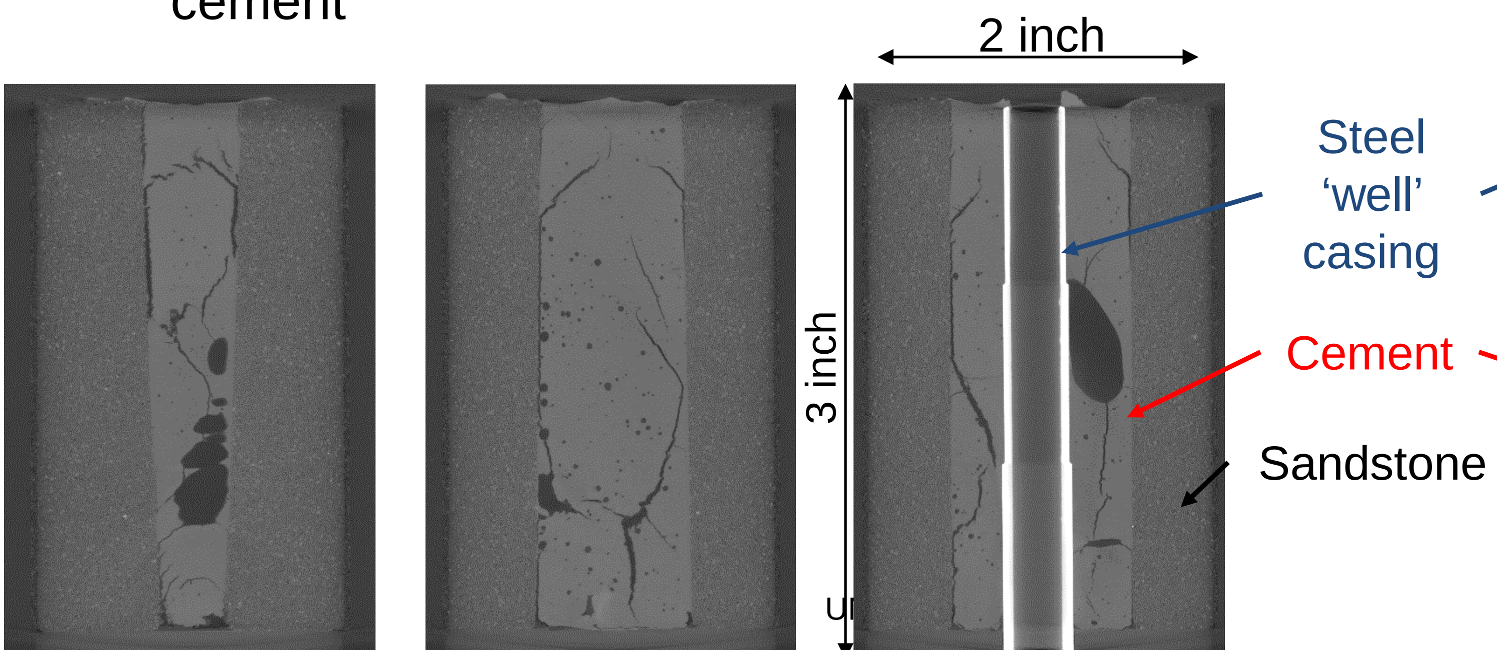


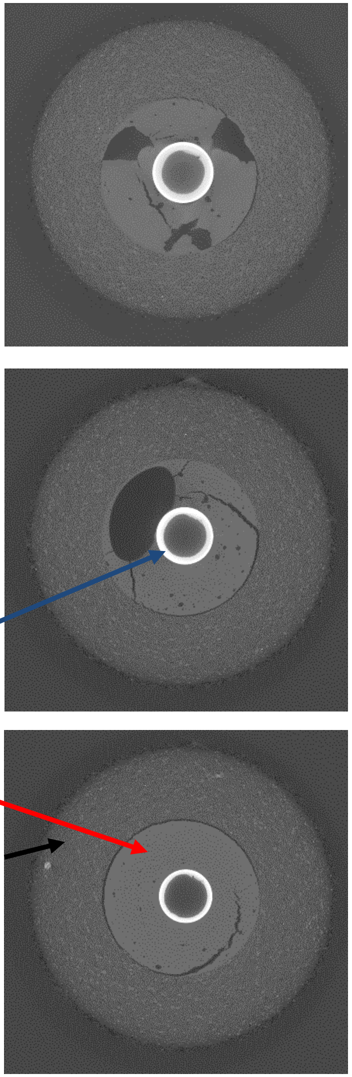
Comparison between the LSRTM imaging for 58 kHz data starting from (a) the initial model (Figure 31b) and (b) the inverted model (Figure 32c).



CT Imaging of Well

- **First CT scans acquired of well/cement/rock system in early 2016**
  - Well thickness varied to ensure minimal imaging artifacts during scanning. Scan resolution 27.8 micron.
  - Multiple voids/fractures created in cement during process to test ability to capture imperfections in cement





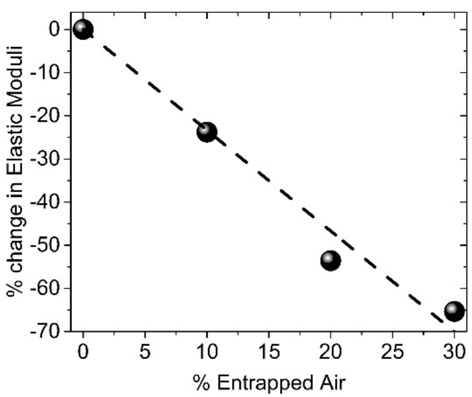
Elastic Properties of Foamed Cement

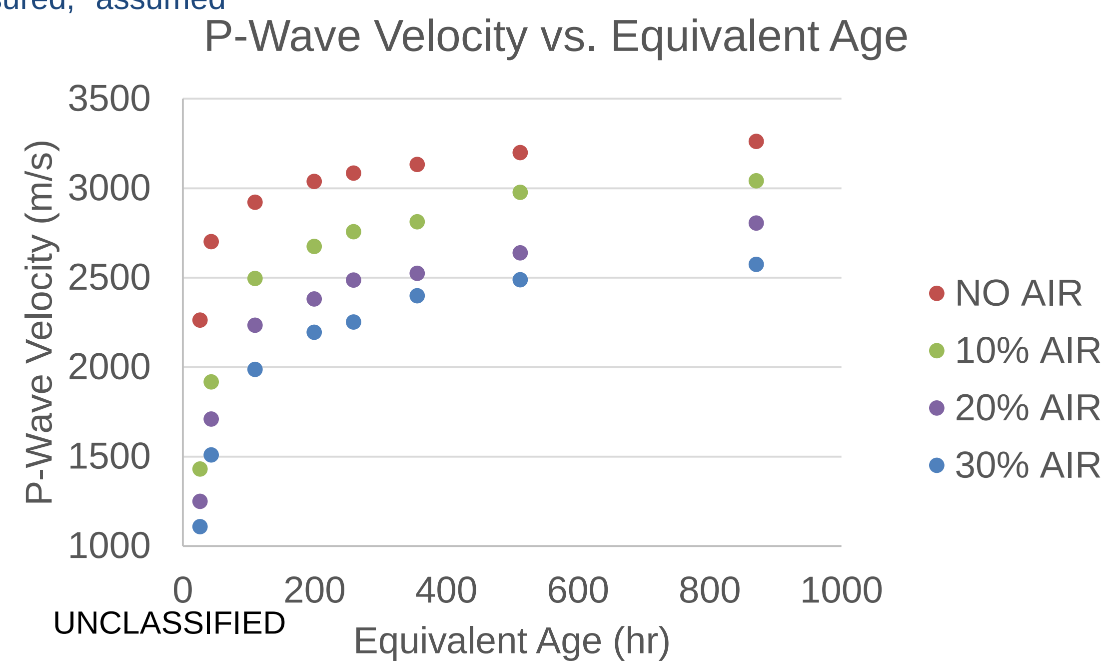
- Ultrasonic testing of Foamed Cement cylinder specimens with size approximately 25 mm (diameter) x 110 mm.

Case (Foam Quality)	0%	10%	20%	30%
P-Wave Velocity⁺ ($^{m}/_{s}$)	3371.5	3060.4	2877.6	2661.8
Mass Density⁺ ($^{kg}/_{m^3}$)	2120.9	1853.2	1650.3	1468.4
Poisson's Ratio*	0.18	0.18	0.19	0.2
Young's Modulus (GPa)	22.2	15.48	11.9	8.8

⁺ measured, *assumed

LANL got similar values.
Poisson ratio was determined to be ~0.25, for both longitudinal and shear propagation modes.
Large change in elastic moduli with air content → significant softening





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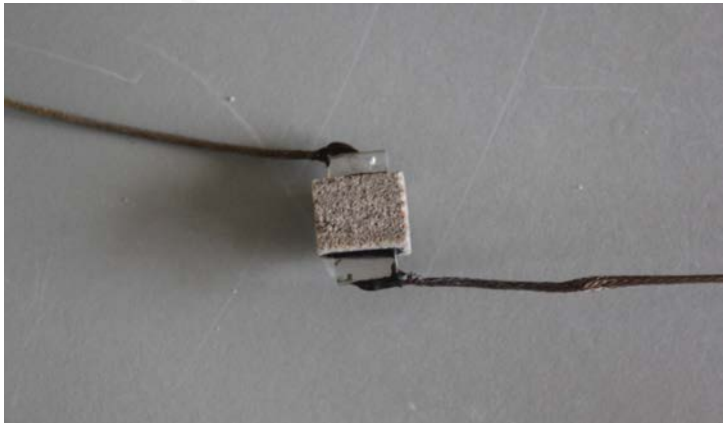
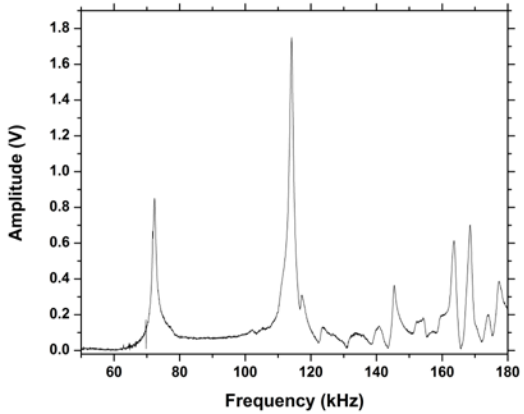
Scientific/Technical Approach
Reservoir Material Study

- Reservoir properties critical for drilling/fracking operations
- Reservoir materials have complex mechanical behavior
- Properties cannot be extrapolated from room temperature
- Resonant Ultrasound Spectroscopy provides ability to measure mechanical properties in extreme conditions



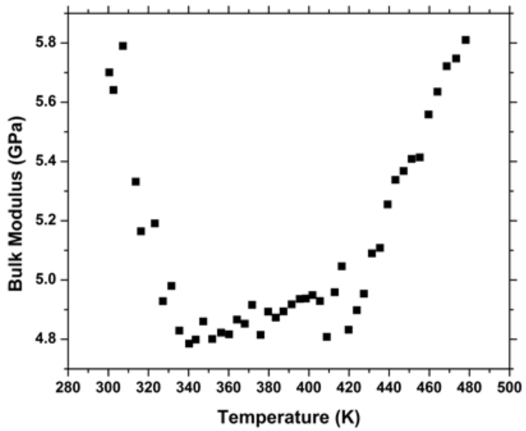
Berea Sandstone sample set for RUS

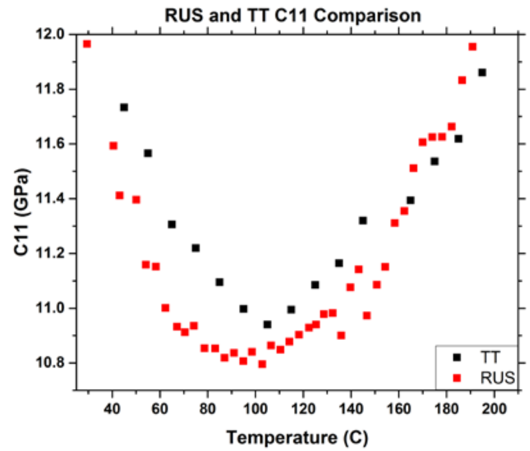


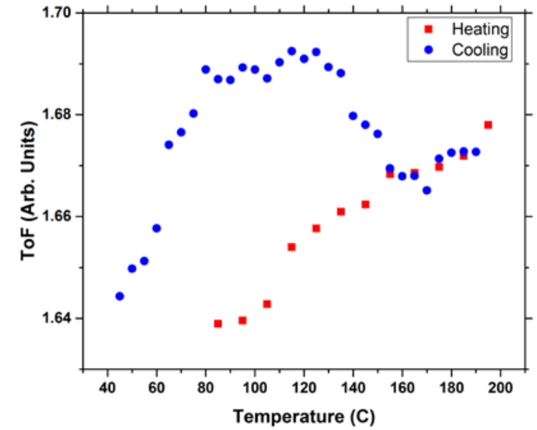
RT RUS spectrum of Berea

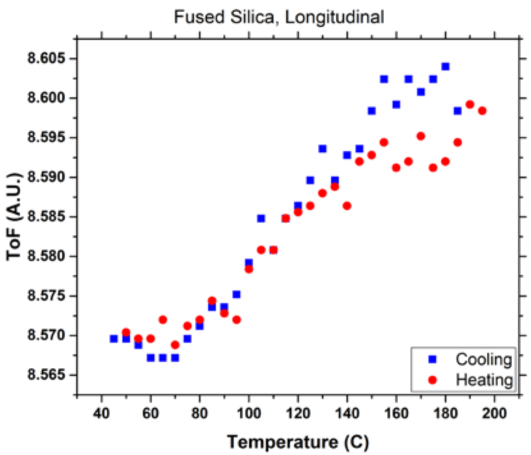
RUS experimental setup

Scientific/Technical Approach
Reservoir Material Study



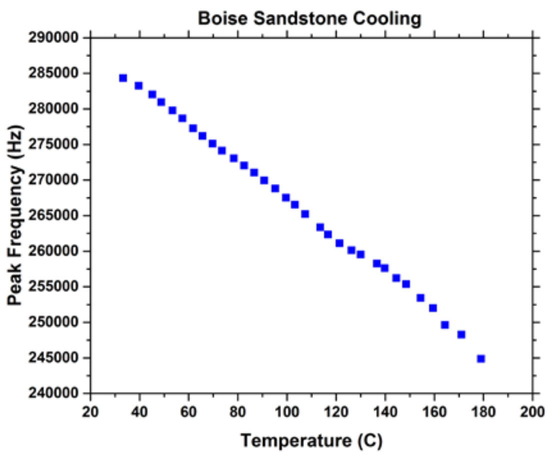


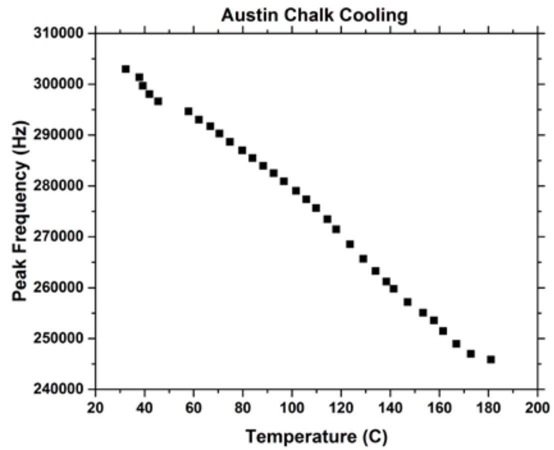


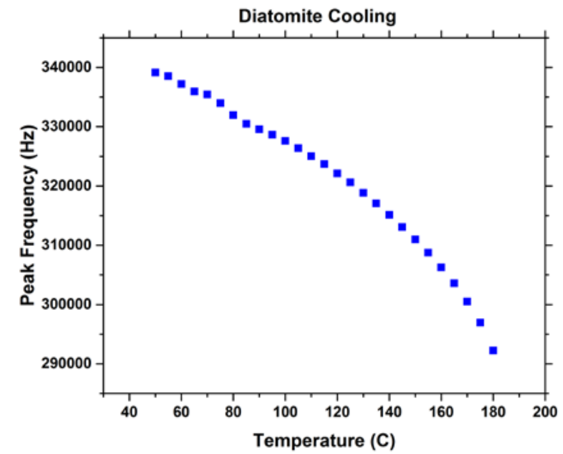


- Bulk modulus of Berea shows anomalous behavior with cooling (top left)
- Through-Transmission experiment confirms result (top middle)
- Berea shows hysteresis with temperature cycling (top right)
- Normal materials do not show this behavior (see left)
- Bonding system is responsible for this behavior as constituents do not show the same (see left)

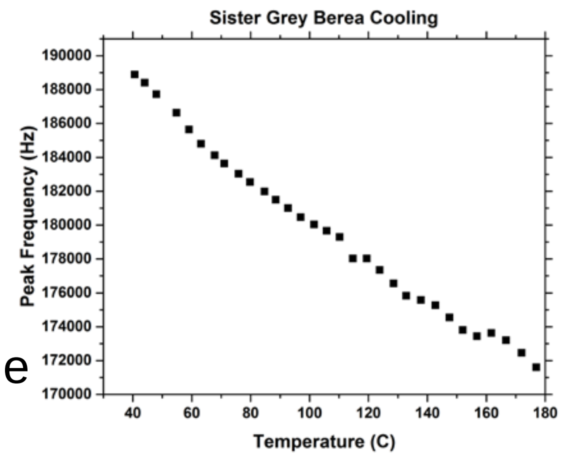
Scientific/Technical Approach
Reservoir Material Study





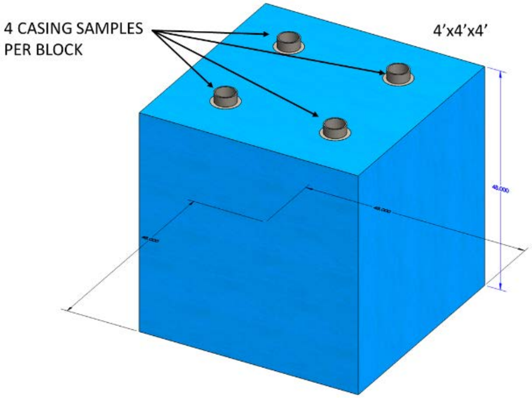


- Other reservoir materials do not necessarily display the same behavior with cooling
- Even other types of Berea might not have anomalous elastic behavior with cooling
- Higher porosity Berea types are more likely to see this behavior
- Drilling and fluid injection can cause thermal shock to the reservoir, causing unpredictable behavior
- It is critical to obtain mechanical properties of reservoir materials in field, not laboratory, conditions!

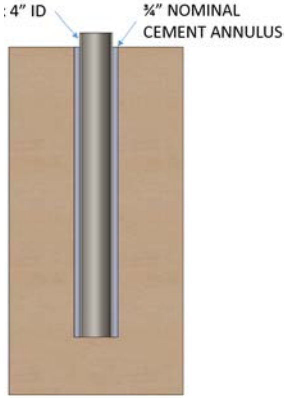


Scientific/Technical Approach
Granite Block Samples – Sandia National Laboratory

Rock sample in drilling facility



4 holes: 6" dia x ~40.5" deep

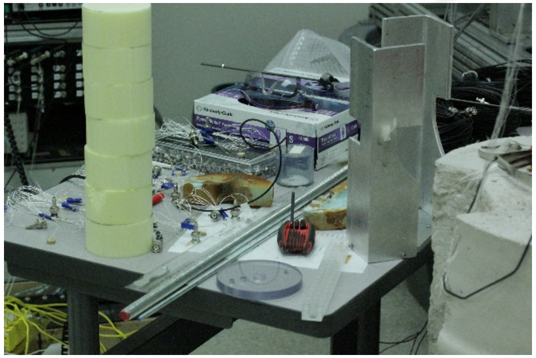


Quartered Granite block

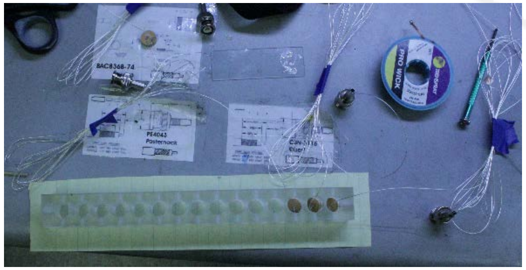
Targeted Casing Defects:

- **Wall thinning**
  - **Pre-machine thin section in casing prior to cementing**
- **Casing eccentricity**
  - **Offset casing with jig during cementing**
- **Channeling**
  - **Removable insert**
- **Delamination**
  - **Thin-layer Silicone insert**

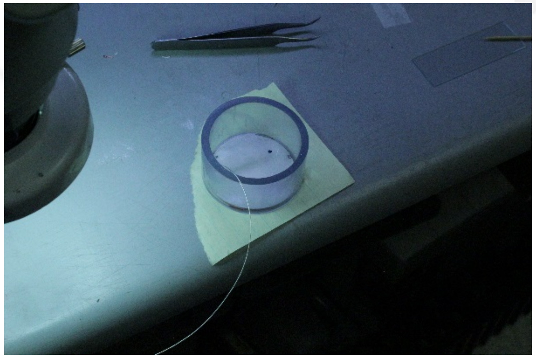
Scientific/Technical Approach
New Streamlined Imaging System



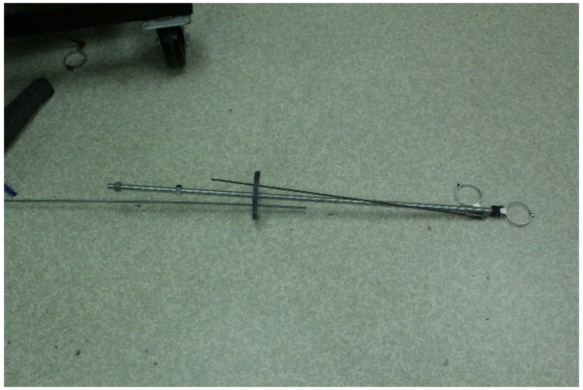
Unassembled Parts



Potting Transducers

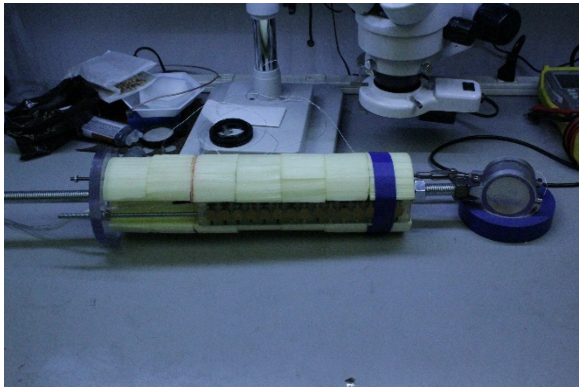


Source Sealed in Plexiglas



Imaging System Shell

Upright and Nearly Assembled



Fully Assembled

Summary

- Built and experimentally validated three different acoustic sources that provide a collimated beam of low frequency.
- Beam collimation is maintained after passing through an inhomogeneous scattering medium (concrete barrel).
- Gained insight in understanding foamed cements, by determining elastic properties and performing CT scans.
- Demonstrated imaging capabilities of the system, in both open- and cased-borehole, for different induced defects (groove, detachment, fluid-filled void pocket, casing).
- Determined a resolution as low as 3 mm.
- Long-term plan: refine and enhance the capabilities of the 3D imaging system for more realistic environments, and extended investigation range beyond the wellbore casing.

Future Directions

Task	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Phase 1 - Feasibility study												
Task 1 – Investigation of existing technology		M2										
Task 2 – Define metrics	M1											
Task 3 – Industry partners/technology maturation plan												
	GoNoGo1											
Phase 2 - Evaluate method on more complex wellbore environments												
Task 1 - Channeling outside casing			M3									
Task 2 - Hardware/software refinement												
Task 3 - Speed-up measurement & analysis												
Task 4 - Method testing on more complex wellbore environments				M4								
Task 5 - Foamed cements manufacturing												
Task 6 - CT of foamed cements												
Task 7 - Acoustics metrics of foamed cements												
Task 8 - Tests on simulated wellbores with foamed cements				M4								
			GoNoGo2									
Phase 3 - Extend method beyond wellbore												
Task 1 - Acoustic source improvement					M5							
Task 2 - Receivers enhancement												
Task 3 - Ruggedized tool							M7					
Task 4 - Image processing refinement						M6						
Task 5 - Technique refinement								M8				
Task 6 - Enhance capabilities for foamed cements												
							GoNoGo3					
							GoNoGo4					
Phase 4 - Technology Development and Verification												
Task 1 - Prototype development									M9			
Task 2 - Prototype verification at lab scale and in field											M11	
Task 3 - Hardware/software enhancement and refinement										M10		

Go/No-Go1 (end Q2Y1)
Tabulate commercial 3D imaging techniques for borehole integrity
- no commercial technologies for high-res 3D imaging technology with similar depth of penetration (~3 m) and resolution (< 5 mm)

Go/NoGo2 (end Y1)
Detect defects at the cement-formation interface, with high resolution- defects detection at the cement-formation interface with a resolution of at least 5 mm

Go/No-Go3 (end Y2)
Tool survival in adverse conditions of corrosiveness, high temperature and high pressure (brines, 250°C, 45 kpsi)
- imaging system can survive in adverse conditions of temperature, pressure and corrosiveness

Go/No-Go4 (end Y2)
Imaging capabilities out in the formation, up to 3 meters
- defects/features (up to ~ 3m) can be resolved in the received signal